US009310323B2

(12) **United States Patent**
Bendahan et al.

(10) **Patent No.: US 9,310,323 B2**
(45) **Date of Patent: Apr. 12, 2016**

(54) **SYSTEMS AND METHODS FOR HIGH-Z THREAT ALARM RESOLUTION**

(71) Applicant: **Rapiscan Systems, Inc.**, Torrance, CA (US)

(72) Inventors: **Joseph Bendahan**, San Jose, CA (US); **Edward James Morton**, Guildford (GB); **David Yaish**, Tel Aviv (IL); **Yossi Kolkovich**, Tel Aviv (IL); **Jacques Goldberg**, Haifa (IL)

(73) Assignee: **Rapiscan Systems, Inc.**, Torrance, CA (US)

(*) Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 0 days.

(21) Appl. No.: **14/516,146**

(22) Filed: **Oct. 16, 2014**

(65) **Prior Publication Data**

US 2015/0108349 A1 Apr. 23, 2015

Related U.S. Application Data

(60) Provisional application No. 61/891,886, filed on Oct. 16, 2013.

(51) **Int. Cl.**

G01J 1/00	(2006.01)
G01N 23/04	(2006.01)
G01V 5/00	(2006.01)

(52) **U.S. Cl.**

CPC ***G01N 23/046*** (2013.01); ***G01V 5/00*** (2013.01); ***G01V 5/0016*** (2013.01)

(58) **Field of Classification Search**

CPC G01V 5/0091; G01T 1/2935; G01T 1/185; H01J 47/02

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,299,251	A	10/1942	Perbal
2,831,123	A	4/1958	Daly
3,707,672	A	12/1972	Miller

(Continued)

FOREIGN PATENT DOCUMENTS

GB	2299251	9/1996
WO	2006095188	9/2006

(Continued)

OTHER PUBLICATIONS

Notice of Allowance dated Jan. 13, 2015 for U.S. Appl. No. 13/858,479.

(Continued)

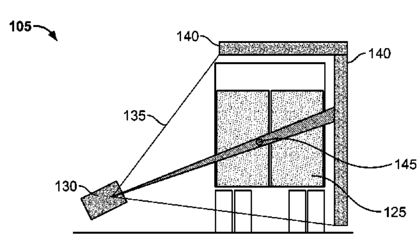
Primary Examiner — Kiho Kim

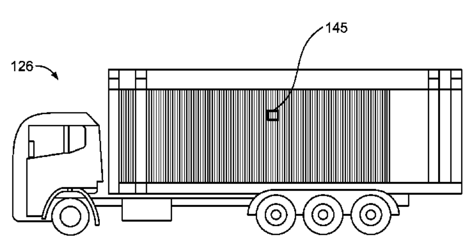
(74) *Attorney, Agent, or Firm* — Novel IP

(57) **ABSTRACT**

A second stage screening system configured to resolve a threat alarm detected in a cargo by a first stage screening system. The second stage screening system includes layers of first muon detectors placed above the cargo to detect a first coordinate and an angle of incidence of incoming muons and layers of second muon detectors placed below the cargo to detect an actual coordinate and an actual angle of exit of the incoming muons. The first and second detectors measure a momentum of the incoming muons. A processing unit receives threat sensitivity vectors determined from the first stage, operates a cargo positioning system that centers a high-Z threat within the cargo, relative to the first and second muon detectors, and analyzes the momentum and a distribution of deflection angles between the angles of incidence and exit to resolve the threat alarm.

46 Claims, 13 Drawing Sheets





(56) **References Cited**

U.S. PATENT DOCUMENTS

3,713,156 A		1/1973	Pothier
3,766,387 A		10/1973	Heffan
3,784,837 A		1/1974	Holmstrom
RE28,544 E		9/1975	Stein
4,047,035 A		9/1977	Dennhoven
4,122,783 A		10/1978	Pretini
4,139,771 A		2/1979	Dennhoven
4,210,811 A		7/1980	Dennhoven
4,216,499 A		8/1980	Dennhoven
4,366,382 A		12/1982	Kotowski
4,399,403 A		8/1983	Strandberg
4,430,568 A		2/1984	Yoshida
4,471,343 A		9/1984	Lemelson
4,566,113 A		1/1986	Donges
4,599,740 A		7/1986	Cable
4,641,330 A		2/1987	Herwig
4,736,401 A		4/1988	Donges
4,754,469 A		6/1988	Harding
4,788,704 A		11/1988	Donges
4,789,930 A		12/1988	Sones
4,825,454 A		4/1989	Annis
4,884,289 A		11/1989	Glockmann
4,956,856 A		9/1990	Harding
4,975,968 A		12/1990	Yukl
4,979,202 A		12/1990	Siczek
4,991,189 A		2/1991	Boomgaarden
5,007,072 A		4/1991	Jenkins
5,008,911 A		4/1991	Harding
5,022,062 A		6/1991	Annis
5,065,418 A		11/1991	Bermbach
5,081,456 A		1/1992	Michiguchi
5,091,924 A		2/1992	Bermbach
5,098,640 A		3/1992	Gozani
5,179,581 A		1/1993	Annis
5,181,234 A		1/1993	Smith
5,182,764 A		1/1993	Peschmann
5,224,144 A		6/1993	Annis
5,227,800 A		7/1993	Huguenin
5,237,598 A		8/1993	Albert
5,247,561 A		9/1993	Kotowski
5,253,283 A		10/1993	Annis
5,263,075 A		11/1993	McGann
5,265,144 A		11/1993	Harding
5,313,511 A		5/1994	Annis
5,339,080 A		8/1994	Steinway
5,345,240 A		9/1994	Frazier
5,367,552 A		11/1994	Peschmann
5,379,334 A		1/1995	Zimmer
5,420,905 A		5/1995	Bertozzi
5,493,596 A		2/1996	Annis
5,524,133 A		6/1996	Neale
5,552,705 A		9/1996	Keller
5,557,283 A		9/1996	Sheen
5,600,303 A		2/1997	Husseiny
5,600,700 A		2/1997	Krug
5,638,420 A		6/1997	Armistead
5,642,393 A		6/1997	Krug
5,642,394 A		6/1997	Rothschild
5,666,393 A		9/1997	Annis
5,687,210 A		11/1997	Maitrejean
5,689,239 A		11/1997	Turner
5,692,028 A		11/1997	Geus
5,745,543 A		4/1998	De
5,751,837 A		5/1998	Watanabe
5,764,683 A		6/1998	Swift
5,768,334 A		6/1998	Maitrejean
5,787,145 A		7/1998	Geus
5,805,660 A		9/1998	Perion
5,838,759 A		11/1998	Armistead
5,903,623 A		5/1999	Swift
5,910,973 A		6/1999	Grodzins
5,930,326 A		7/1999	Rothschild
5,940,468 A		8/1999	Huang
5,974,111 A	*	10/1999	Krug et al. 378/57
6,026,135 A		2/2000	McFee
6,031,890 A		2/2000	Bermbach
6,054,712 A		4/2000	Komardin
6,058,158 A		5/2000	Eiler
6,067,344 A		5/2000	Grodzins
6,081,580 A		6/2000	Grodzins
6,094,472 A		7/2000	Smith
6,115,128 A		9/2000	Vann
6,118,850 A		9/2000	Mayo
6,128,365 A		10/2000	Bechwati
6,151,381 A		11/2000	Grodzins
6,184,841 B1		2/2001	Shober
6,188,743 B1		2/2001	Tybinkowski
6,188,747 B1		2/2001	Geus
6,192,101 B1		2/2001	Grodzins
6,192,104 B1		2/2001	Adams
6,195,413 B1		2/2001	Geus
6,198,795 B1		3/2001	Naumann
6,216,540 B1		4/2001	Nelson
6,218,943 B1		4/2001	Ellenbogen
6,249,567 B1		6/2001	Rothschild
6,252,929 B1		6/2001	Swift
6,256,369 B1		7/2001	Lai
6,278,115 B1		8/2001	Annis
6,282,260 B1		8/2001	Grodzins
6,288,676 B1		9/2001	Maloney
6,292,533 B1		9/2001	Swift
6,301,326 B2		10/2001	Bjorkholm
6,320,933 B1		11/2001	Grodzins
6,342,696 B1		1/2002	Chadwick
6,356,620 B1		3/2002	Rothschild
6,359,582 B1		3/2002	MacAleese
6,359,597 B2		3/2002	Haj-Yousef
6,417,797 B1		7/2002	Cousins
6,424,695 B1		7/2002	Grodzins
6,434,219 B1		8/2002	Rothschild
6,435,715 B1		8/2002	Betz
6,442,233 B1		8/2002	Grodzins
6,445,765 B1		9/2002	Frank
6,453,003 B1		9/2002	Springer
6,453,007 B2		9/2002	Adams
6,456,093 B1		9/2002	Merkel
6,456,684 B1		9/2002	Mun
6,459,761 B1		10/2002	Grodzins
6,459,764 B1		10/2002	Chalmers
6,469,624 B1		10/2002	Whan
6,473,487 B1		10/2002	Le
RE37,899 E		11/2002	Grodzins
6,480,141 B1		11/2002	Toth
6,483,894 B2		11/2002	Hartick
6,501,414 B2		12/2002	Arndt
6,507,025 B1		1/2003	Verbinski
6,532,276 B1		3/2003	Hartick
6,542,574 B2		4/2003	Grodzins
6,542,578 B2		4/2003	Ries
6,542,580 B1		4/2003	Carver
6,546,072 B1		4/2003	Chalmers
6,552,346 B2		4/2003	Verbinski
6,563,903 B2		5/2003	Kang
6,580,778 B2		6/2003	Meder
6,584,170 B2		6/2003	Aust
6,597,760 B2		7/2003	Beneke
6,606,516 B2		8/2003	Levine
6,628,745 B1		9/2003	Annis
6,636,581 B2		10/2003	Sorenson
6,650,276 B2		11/2003	Lawless
6,653,588 B1		11/2003	Gillard-Hickman
6,658,087 B2		12/2003	Chalmers
6,663,280 B2		12/2003	Doenges
6,665,373 B1		12/2003	Kotowski
6,665,433 B2		12/2003	Roder
6,735,477 B2		5/2004	Levine
6,763,635 B1		7/2004	Lowman
6,765,527 B2		7/2004	Jablonski
6,768,317 B2		7/2004	Moeller
6,785,357 B2		8/2004	Bernardi
6,796,944 B2		9/2004	Hall
6,798,863 B2		9/2004	Sato
6,812,426 B1		11/2004	Kotowski
6,816,571 B2		11/2004	Bijjani

(56) **References Cited**

U.S. PATENT DOCUMENTS

6,831,590	B1	12/2004	Steinway
6,837,422	B1	1/2005	Meder
6,839,403	B1	1/2005	Kotowski
6,843,599	B2	1/2005	Le
6,856,271	B1	2/2005	Hausner
6,876,322	B2	4/2005	Keller
6,891,381	B2	5/2005	Bailey
6,894,636	B2	5/2005	Anderton
6,920,197	B2	7/2005	Kang
6,922,460	B2	7/2005	Skatter
6,928,141	B2	8/2005	Carver
7,039,159	B2	5/2006	Muenchau
7,092,485	B2	8/2006	Kravis
7,207,713	B2	4/2007	Lowman
7,322,745	B2	1/2008	Agrawal
7,356,115	B2	4/2008	Ford
7,366,282	B2	4/2008	Peschmann
7,369,643	B2	5/2008	Kotowski
7,417,440	B2	8/2008	Peschmann
7,492,228	B2	2/2009	Strange
7,579,845	B2	8/2009	Peschmann
7,606,348	B2	10/2009	Foland
7,609,807	B2	10/2009	Leue
7,652,254	B2	1/2010	Shpantzer
7,701,336	B1	4/2010	Willms
7,714,297	B2	5/2010	Morris
7,831,012	B2	11/2010	Foland
7,838,841	B2	11/2010	Morris
7,856,081	B2	12/2010	Peschmann
7,908,121	B2	3/2011	Green
7,945,105	B1	5/2011	Jaenisch
8,138,770	B2	3/2012	Peschmann
8,247,767	B2	8/2012	Morris
8,274,377	B2	9/2012	Smith
8,288,721	B2	10/2012	Morris
8,428,217	B2	4/2013	Peschmann
8,513,601	B2	8/2013	Morris
8,536,527	B2	9/2013	Morris
8,552,370	B2	10/2013	Schultz
8,674,706	B2	3/2014	Peschmann
8,975,593	B1 *	3/2015	Best et al. 250/391
9,042,511	B2	5/2015	Peschmann
9,268,058	B2	2/2016	Peschmann
2002/0008655	A1	1/2002	Haj-Yousef
2003/0009202	A1	1/2003	Levine
2003/0179126	A1	9/2003	Jablonski
2003/0216644	A1	11/2003	Hall
2004/0057042	A1 *	3/2004	Ovadia 356/237.1
2004/0077943	A1	4/2004	Meaney
2004/0141584	A1	7/2004	Bernardi
2005/0058242	A1	3/2005	Peschmann
2005/0104603	A1	5/2005	Peschmann
2005/0117700	A1	6/2005	Peschmann
2005/0180542	A1	8/2005	Leue
2005/0275545	A1	12/2005	Alioto
2006/0145771	A1	7/2006	Strange
2008/0315091	A1 *	12/2008	Morris et al. 250/307
2009/0295576	A1	12/2009	Shpantzer
2009/0321653	A1 *	12/2009	Perticone et al. 250/393
2011/0051996	A1	3/2011	Gudmundson
2011/0089332	A1	4/2011	Ivan
2012/0261572	A1	10/2012	Schmidt
2012/0312985	A1	12/2012	Morris
2013/0039462	A1 *	2/2013	Morton 378/57
2013/0081451	A1 *	4/2013	Kamada et al. 73/65.01
2013/0294574	A1	11/2013	Peschmann
2014/0319365	A1	10/2014	Sossong
2015/0133787	A1	5/2015	Wegner
2015/0212014	A1	7/2015	Sossong
2015/0241593	A1	8/2015	Blanpied
2015/0246244	A1	9/2015	Sossong
2015/0279489	A1	10/2015	Milner
2015/0287237	A1	10/2015	Bai
2015/0325013	A1	11/2015	Patnaik
2016/0025888	A1	1/2016	Peschmann
2016/0041297	A1	2/2016	Blanpied

FOREIGN PATENT DOCUMENTS

WO	2011008718	1/2011
WO	WO 2011008718 A1 *	1/2011
WO	2015038554	3/2015
WO	2015057973	4/2015

OTHER PUBLICATIONS

Sheen, David et al. 'Three-Dimensional Millimeter-Wave Imaging for Concealed Weapon Detection', Sep. 2001, IEEE Transactions on Microwave Theory and Techniques, vol. 49, No. 9, pp. 1581-1592.

Office Action dated Mar. 18, 2015 for U.S. Appl. No. 14/165,177.

Notice of Allowance dated Aug. 20, 2015 for U.S. Appl. No. 14/165,177.

International Search Report for PCT/US14/60914, mailed on Feb. 4, 2015, Rapiscan Systems Inc.

Hasuko et al, "The First Integration Test of the Atlas End-Cap Muon Level 1 Trigger System", IEEE Transactions on Nuclear Science, vol. 50, No. 4, Aug. 2003 (2003), pp. 864-868.

Cortesi et al, "Investigations of a THGEM-based imaging detector", Institute of Physics Publishing and SISSA, Sep. 4, 2007.

Blanpied et al, "Material discrimination using scattering and stopping of cosmis ray muons and electrons: Differentiating heavier from lighter metals as well as low-atomic weight materials", Nuclear Instruments and Methods in Physics Research A, 784 (2015) 352-358.

* cited by examiner

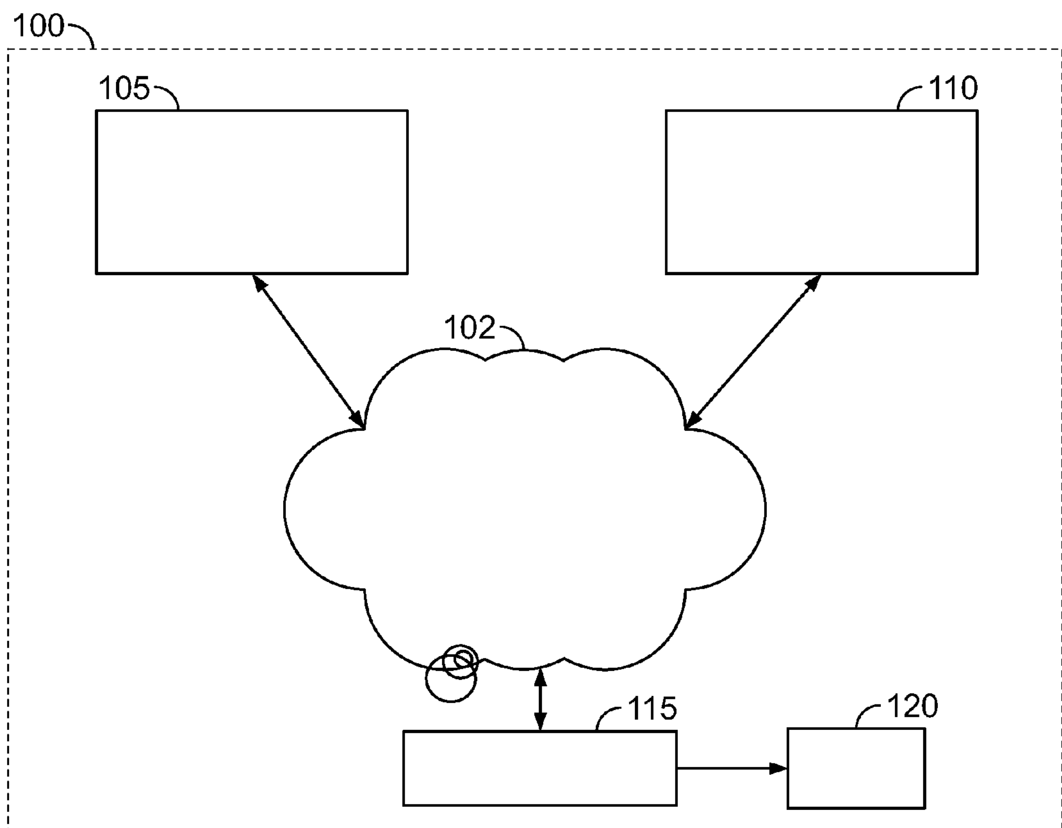


FIG. 1A

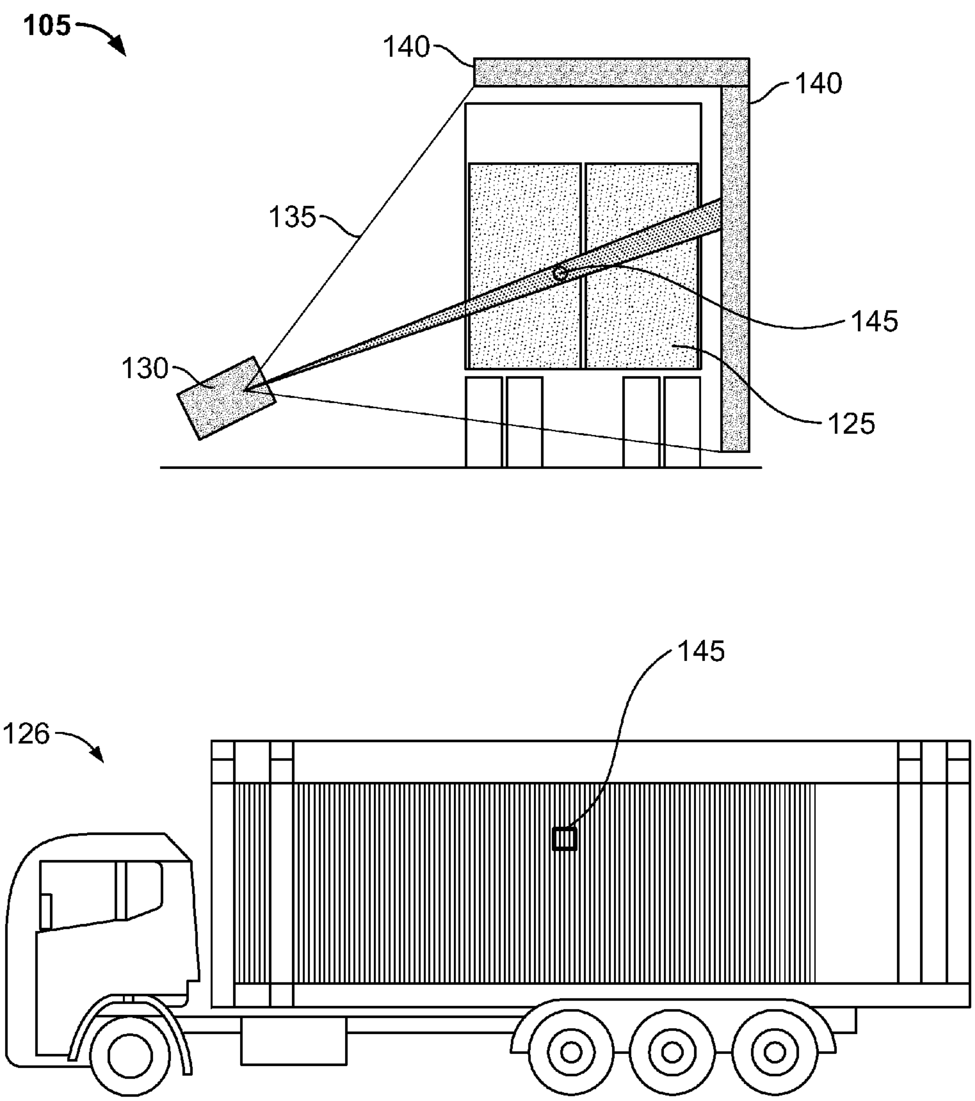


FIG. 1B

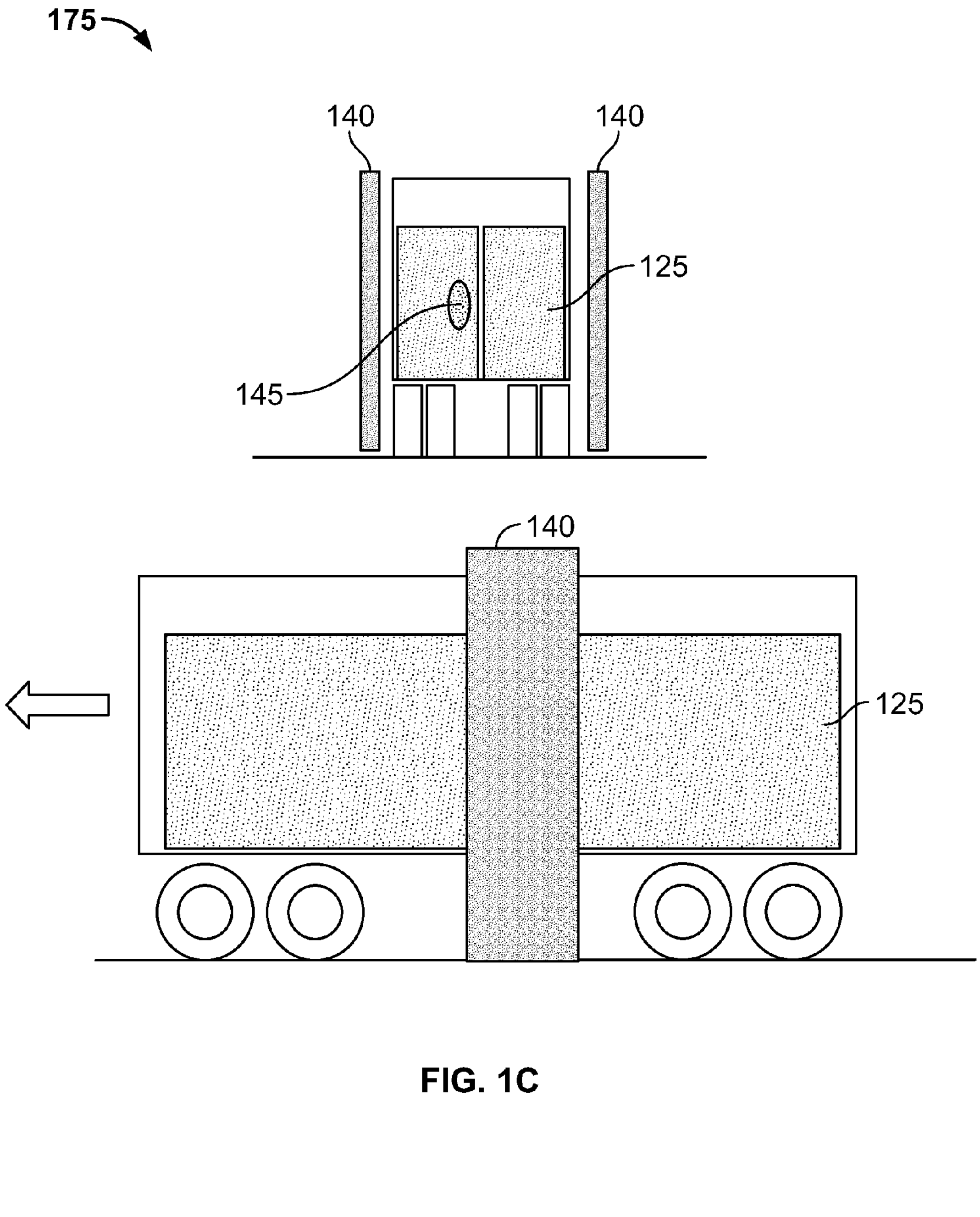


FIG. 1C

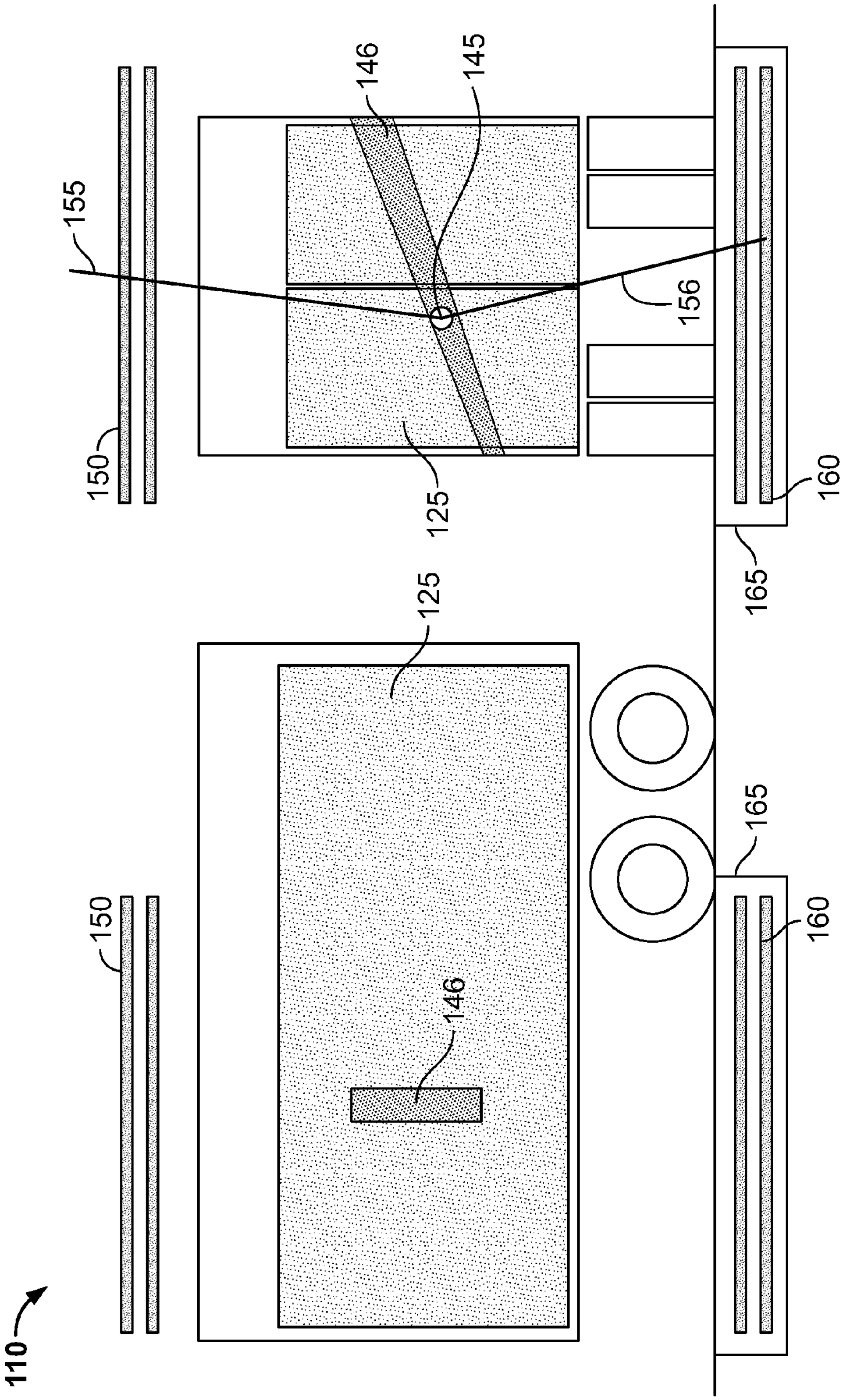


FIG. 1D

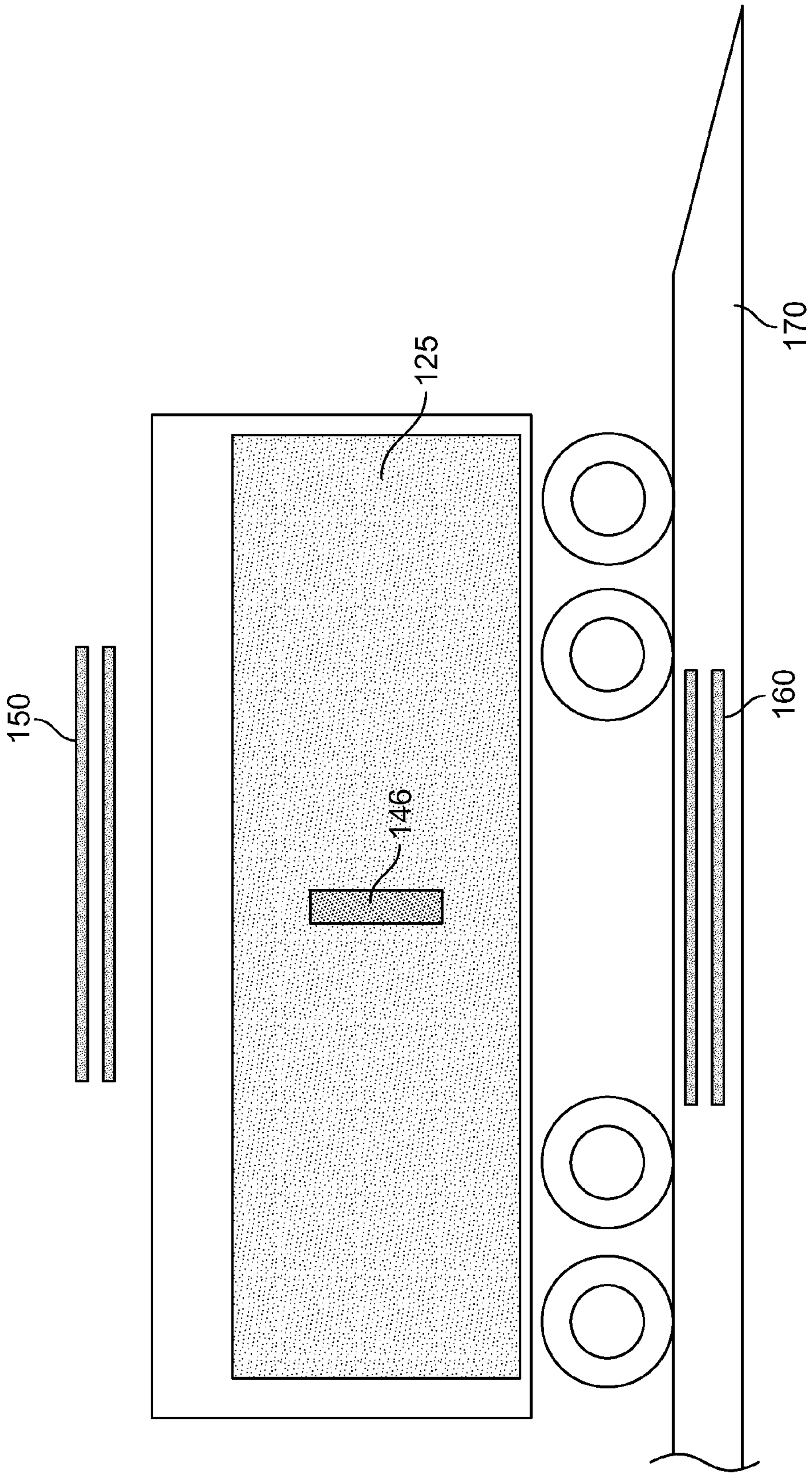


FIG. 1E

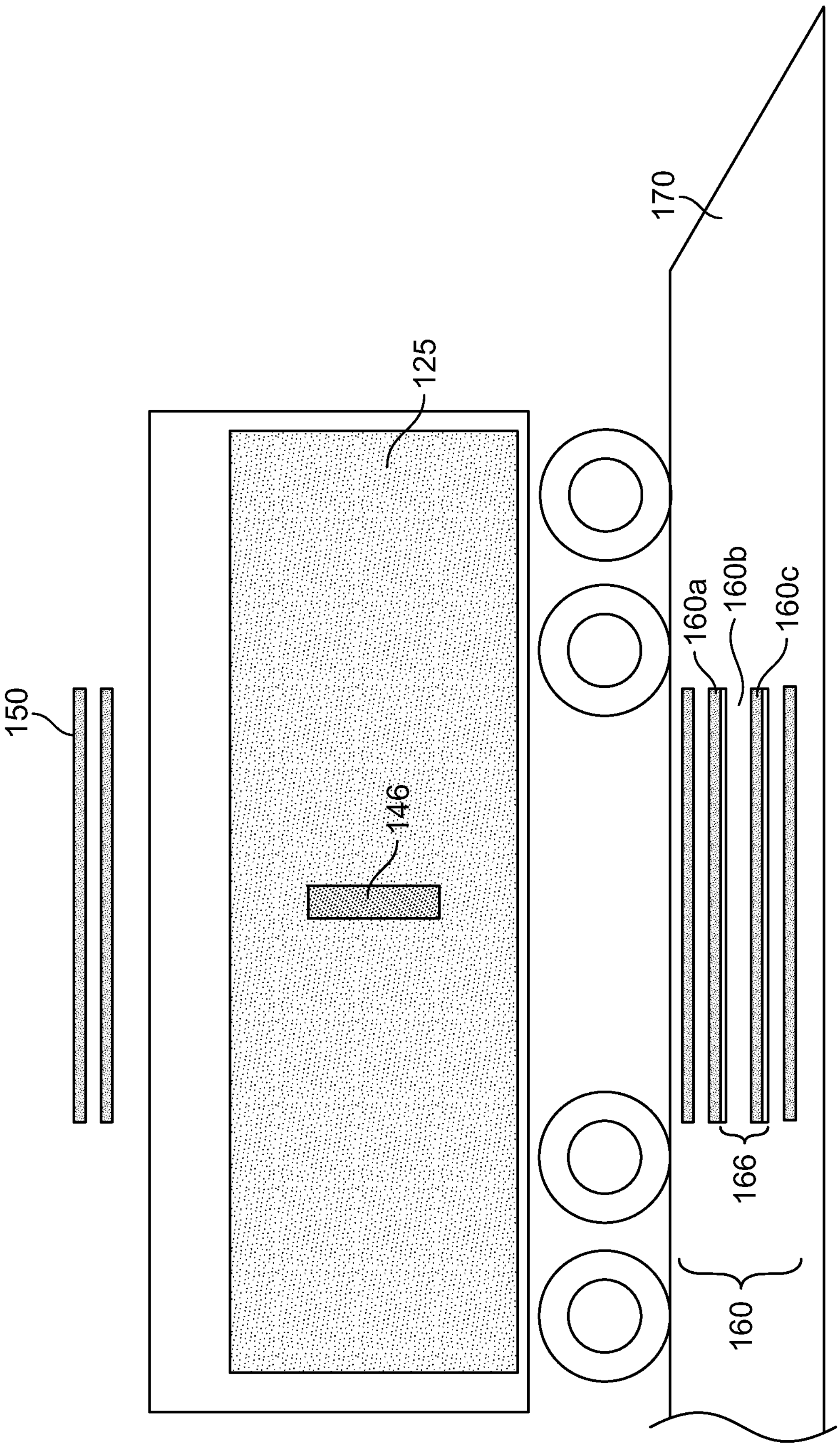


FIG. 1F

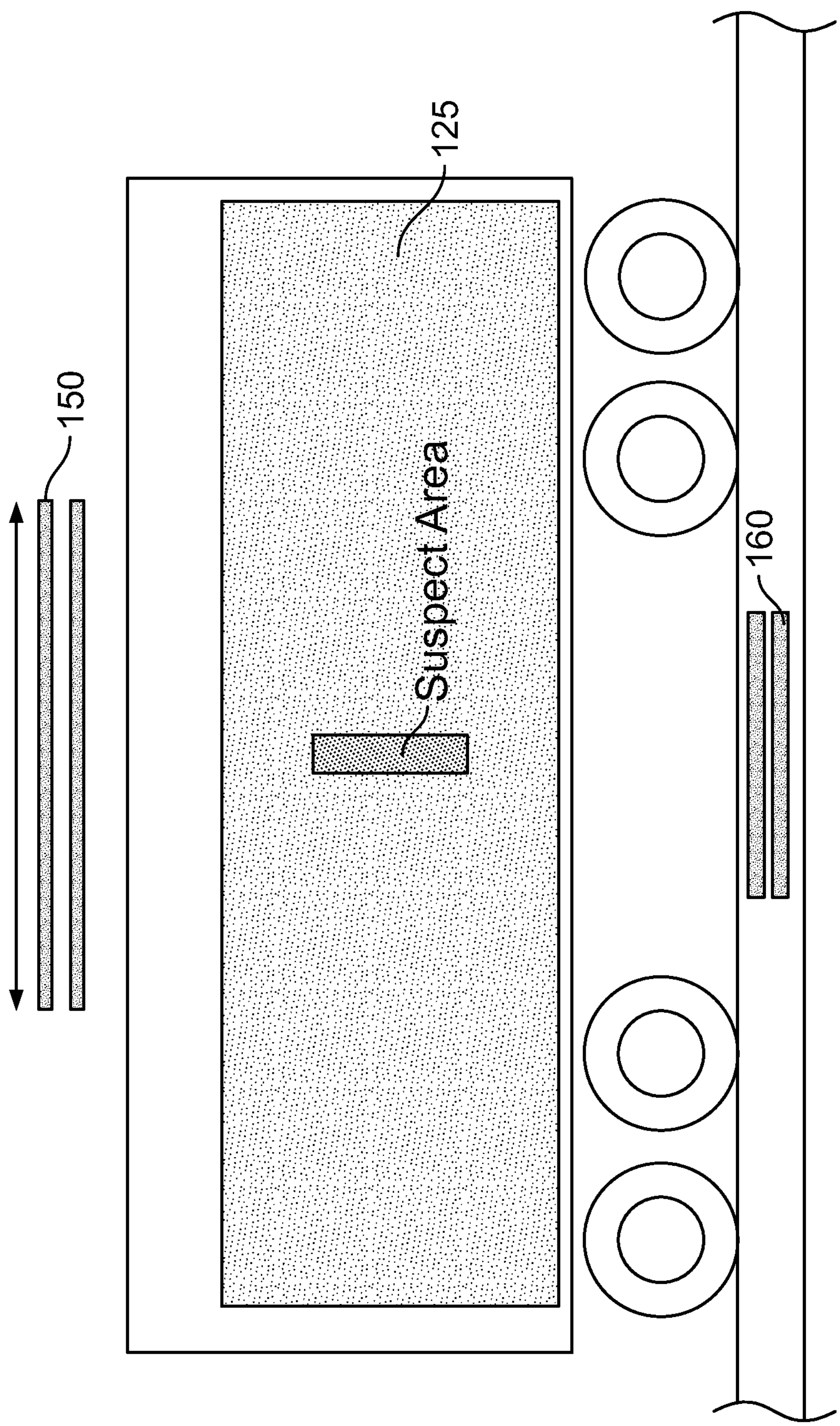


FIG. 1G

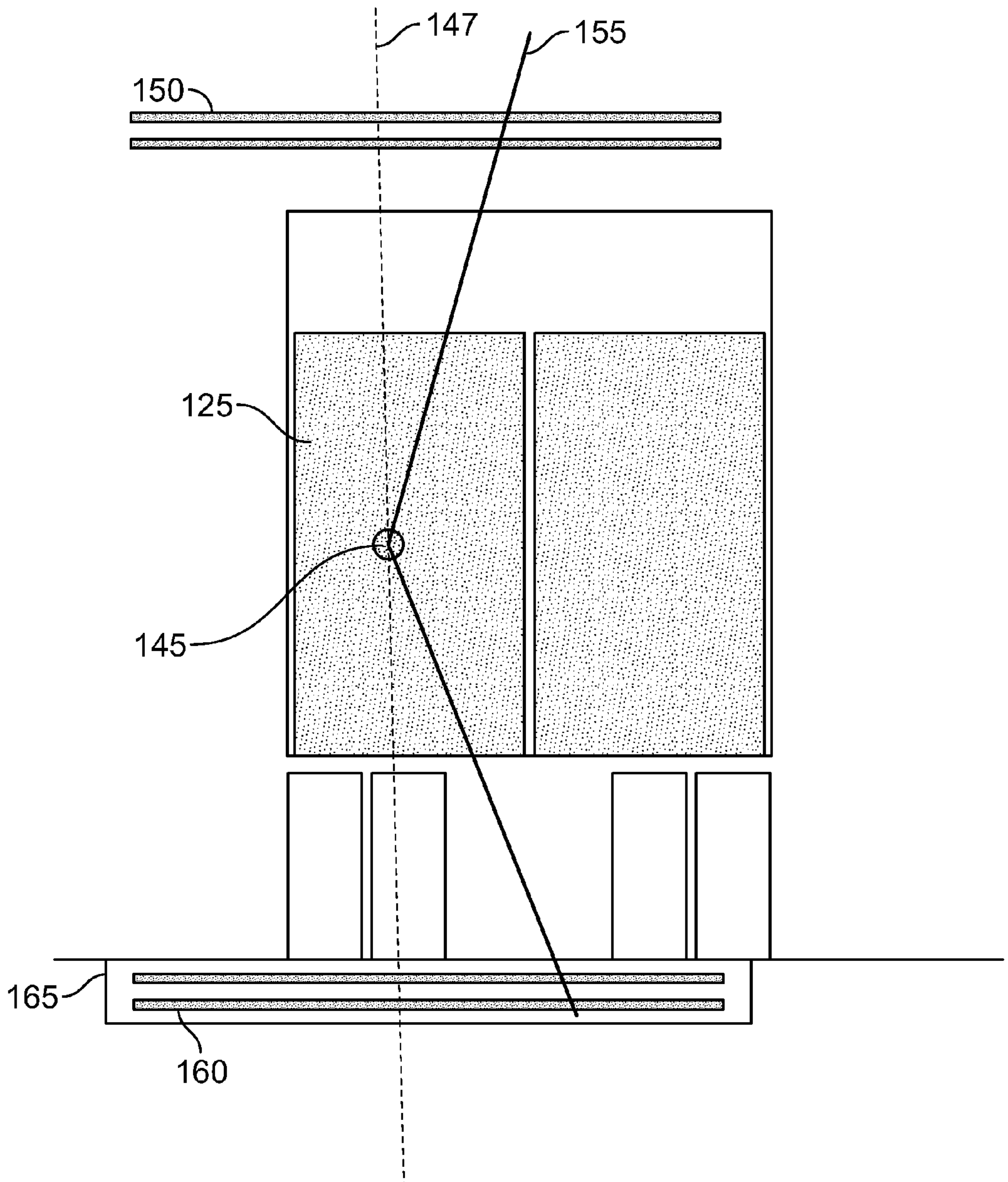


FIG. 1H

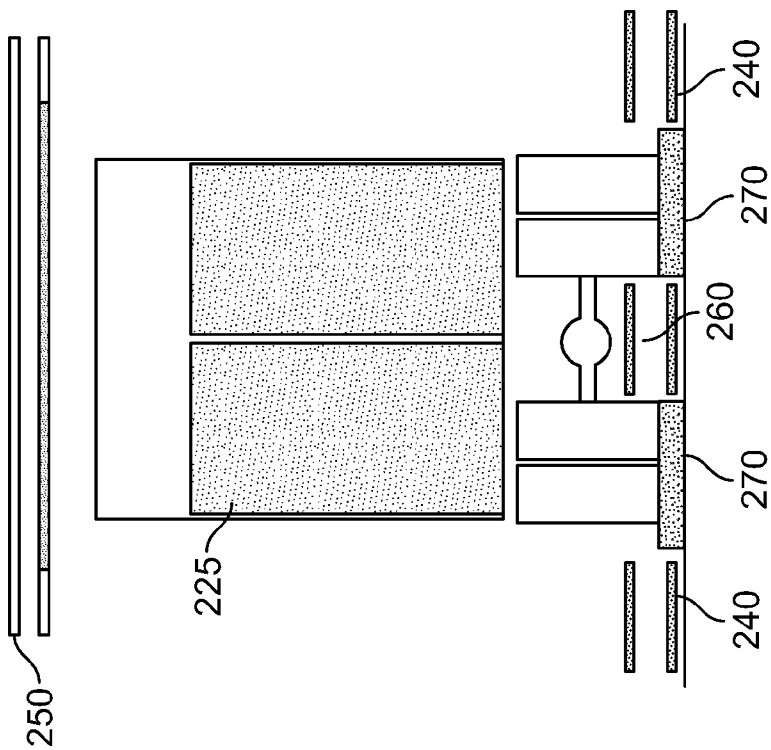


FIG. 2B

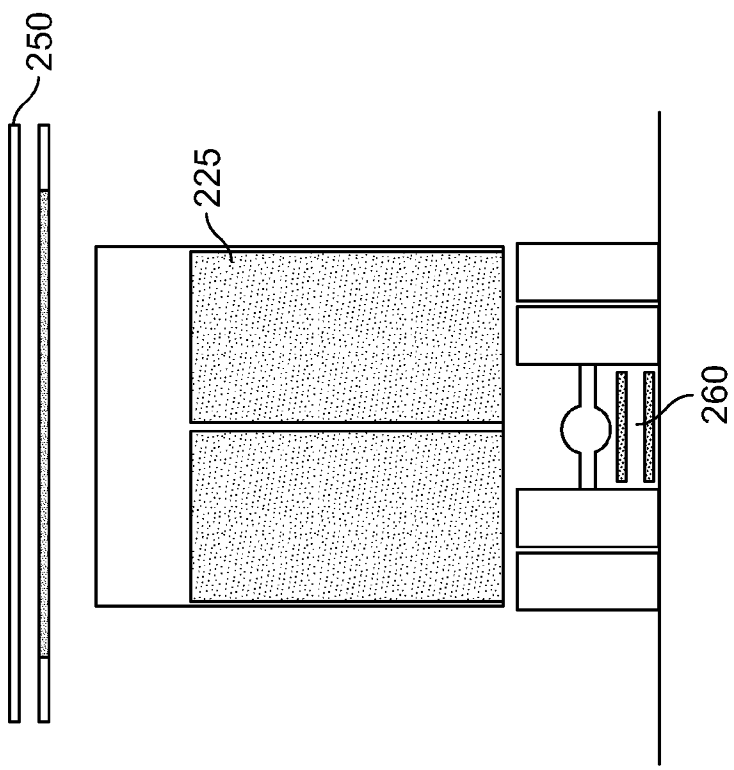


FIG. 2A

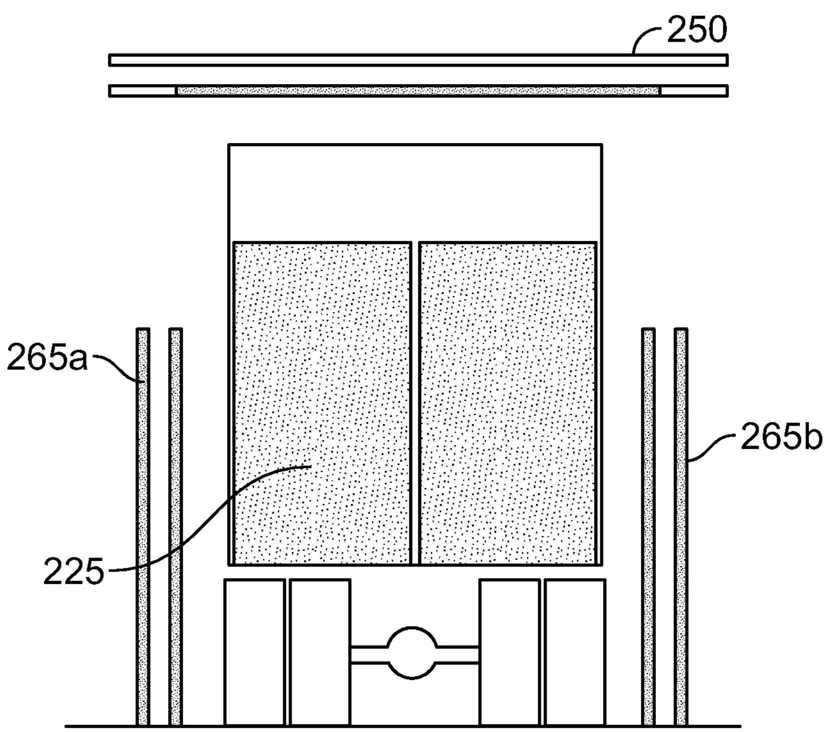


FIG. 2C

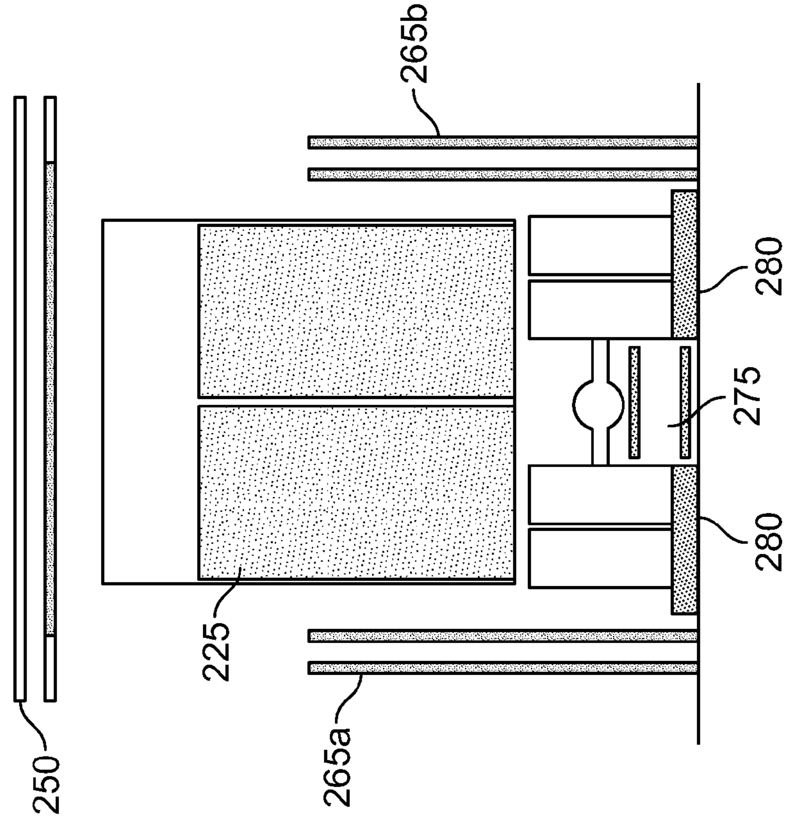


FIG. 2E

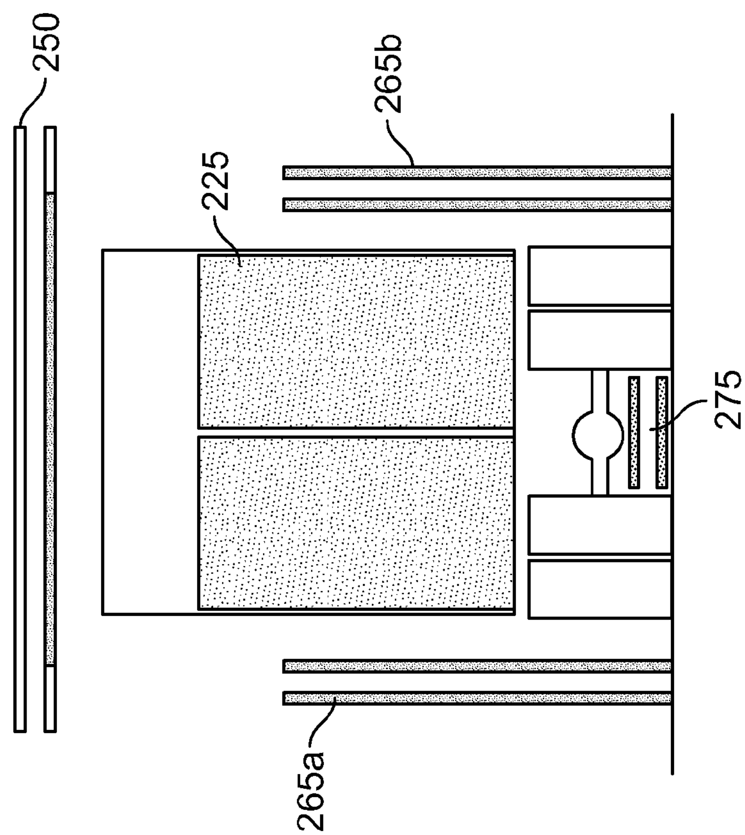


FIG. 2D

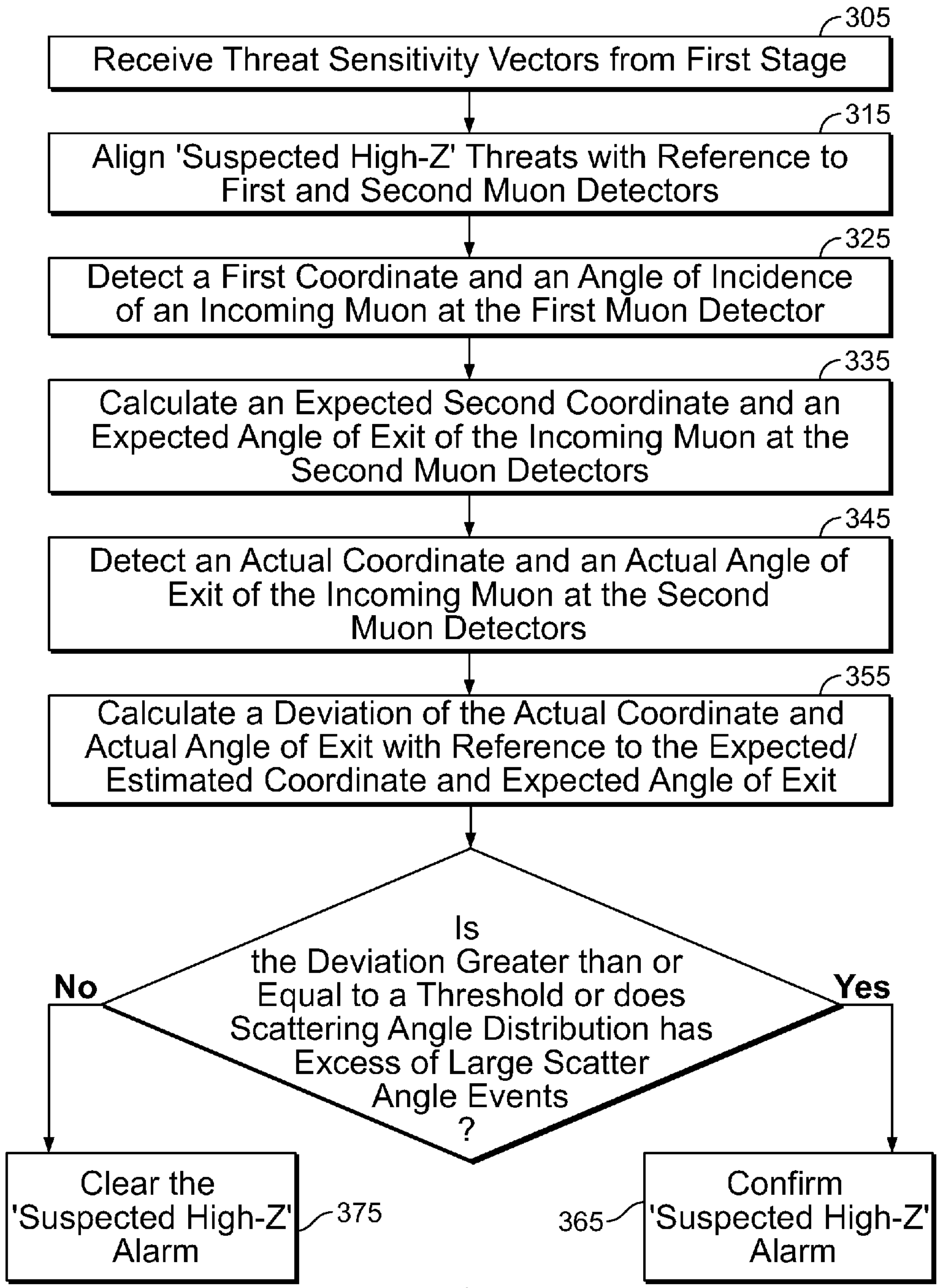

305
Receive Threat Sensitivity Vectors from First Stage
315
Align 'Suspected High-Z' Threats with Reference to First and Second Muon Detectors
325
Detect a First Coordinate and an Angle of Incidence of an Incoming Muon at the First Muon Detector
335
Calculate an Expected Second Coordinate and an Expected Angle of Exit of the Incoming Muon at the Second Muon Detectors
345
Detect an Actual Coordinate and an Actual Angle of Exit of the Incoming Muon at the Second Muon Detectors
355
Calculate a Deviation of the Actual Coordinate and Actual Angle of Exit with Reference to the Expected/ Estimated Coordinate and Expected Angle of Exit
Is the Deviation Greater than or Equal to a Threshold or does Scattering Angle Distribution has Excess of Large Scatter Angle Events ?
No
Yes
Clear the 'Suspected High-Z' Alarm
375
365
Confirm 'Suspected High-Z' Alarm

FIG. 3

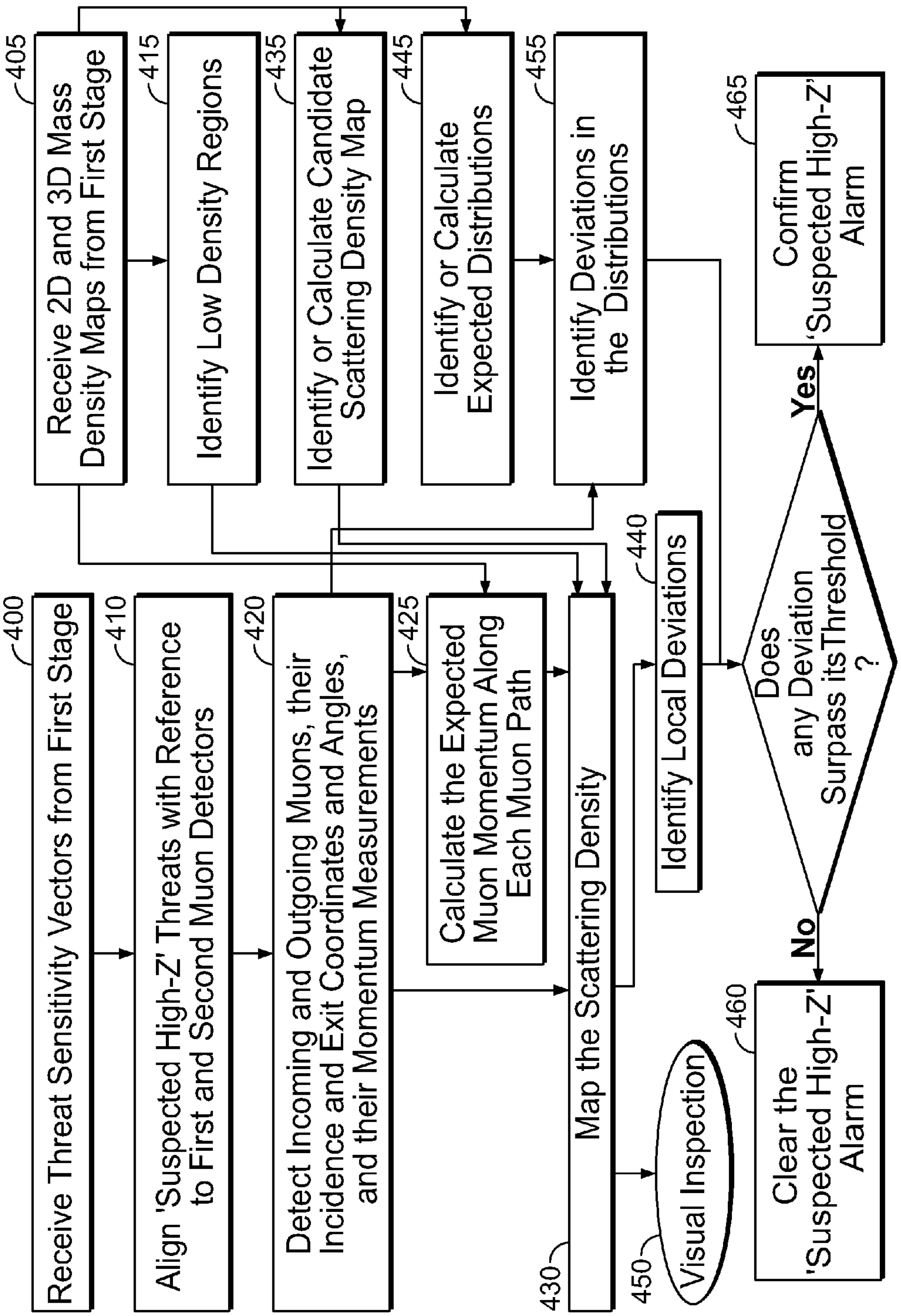

400
Receive Threat Sensitivity Vectors from First Stage
410
Align 'Suspected High-Z' Threats with Reference to First and Second Muon Detectors
420
Detect Incoming and Outgoing Muons, their Incidence and Exit Coordinates and Angles, and their Momentum Measurements
425
Calculate the Expected Muon Momentum Along Each Muon Path
430
Map the Scattering Density
440
Identify Local Deviations
450
Visual Inspection
405
Receive 2D and 3D Mass Density Maps from First Stage
415
Identify Low Density Regions
435
Identify or Calculate Candidate Scattering Density Map
445
Identify or Calculate Expected Distributions
455
Identify Deviations in the Distributions
Does any Deviation Surpass itsThreshold ?
Yes
No
465
Confirm 'Suspected High-Z' Alarm
460
Clear the 'Suspected High-Z' Alarm

FIG. 4

SYSTEMS AND METHODS FOR HIGH-Z THREAT ALARM RESOLUTION

CROSS-REFERENCE

The present application relies on U.S. Provisional Patent Application No. 61/891,886, entitled "High-Z Threat Alarm Resolution System and Method", and filed on Oct. 16, 2013, for priority, which is herein incorporated by reference in its entirety.

The present application is also related to U.S. patent application Ser. No. 14/104,625, entitled "Systems and Methods for Automated, Rapid Detection of High-Atomic Number Materials", and filed on Dec. 12, 2013, which is a continuation of U.S. patent application Ser. No. 12/780,910, of the same title and filed on May 16, 2010 and now U.S. Pat. No. 8,633,823, issued on Jan. 21, 2014, which, in turn, relies on U.S. Provisional Patent Application No. 61/178,945, filed on May 16, 2009.

In addition, the present application is related to U.S. Pat. Nos. 5,638,420; 6,567,496; 6,785,357; 7,322,745; 7,368,717; and 7,526,064.

All of the above-mentioned patents and patent applications are herein incorporated by reference in their entirety.

FIELD

This specification relates generally to systems for detecting and confirming the presence of high atomic number (high-Z) threats, including shielded and un-shielded special nuclear materials (SNM) and shielded radioactive sources. More particularly, this specification relates to a muon detection system deployed as a second stage of cargo inspection and that uses a plurality of threat sensitivity vectors determined from a first stage of inspection to efficiently and effectively resolve threat alarms.

BACKGROUND

It is a constant challenge to assess the contents of cargo containers using non-intrusive methods. The desire to do so is often fueled by the need to detect contraband and the threats posed, for example, by nuclear weapons. There is a need, therefore, to detect high-Z materials characteristic of shielded radioactive sources and unshielded/shielded special nuclear materials.

Radiation Portal Monitors (RPMs) can detect unshielded or lightly shielded radioactive materials in lightly loaded cargos. However, RPMs cannot detect radioactive sources shielded by high-Z materials, or partially shielded radioactive sources and Uranium-235 in medium-to-heavy cargo. High-energy X-ray inspection systems are widely deployed to detect general contraband and more recently, they have been used to detect shielded and unshielded nuclear materials in cargo.

Current research includes employing Muon Tomography (MT) as a primary inspection system and method for detecting special nuclear materials and shielded radioactive materials. A muon is a charged particle with a mass of 206 times that of the electron with a charge of −1. It has a lifetime of around 6 microseconds, which gives it just enough time to get from the outer edge of the atmosphere, where they are created due to interaction of very energetic protons which arrive at the Earth after travelling billions of miles through deep space, to the surface of the Earth where we can use them for imaging.

Muons are minimum ionizing particles—they lose a bit of their energy by collision with atomic electrons. Thus, the

muon travels in a substantially forward direction after each collision, but with a small deviation to the left or the right. After very many collisions, the amplitude of the total deflection from the original direction increases, and this angle of deflection is weakly dependent on the Z (atomic) number of the materials through which the muon is travelling. By measuring the direction of the muon entering a volume and the direction of the muon as it exits the volume, we can draw a line from the point of entrance in the correct direction into the volume and the point of exit in the direction back into the volume and the point of intersection between the two gives the effective center of the scattering material.

However, for detection using Muon Tomography (MT) as a primary inspection system, the throughput is low compared to that for X-ray systems (few minutes vs. tens of seconds). These systems require large detectors that extend the complete object under inspection, which makes the systems expensive and more complex. Also the systems do not provide high-resolution images used to detect general contraband by customs agencies.

Once a high-Z material is detected by a primary system, there is a need to confirm whether the material is fissile. The standard method used for confirmation is based on active interrogation, namely using neutron and/or high-energy sources to induce fission and array of gamma-ray and/or neutrons detectors to detect the radiation emitted from the fission process. However, these systems are complex, expensive, and produce high radiation requiring either a large exclusion zone or a shielded facility.

Therefore, there is a need for a secondary or second stage low-cost system to confirm the presence of shielding and nuclear materials with high confidence in a relatively short time, and with a small exclusion zone compatible with port environments, thereby enabling wide deployment.

SUMMARY

The following embodiments and aspects thereof are described and illustrated in conjunction with systems, tools and methods, which are meant to be exemplary and illustrative, not limiting in scope.

The present specification discloses a second stage screening system to resolve a threat alarm detected in a cargo by a first stage screening system, wherein said first stage screening system generates threat sensitivity vectors, said second stage system comprising: a first muon detector set placed above the cargo to generate first muon information comprising a first coordinate and an angle of incidence of incoming muons; a second muon detector set placed below the cargo to generate second muon information comprising an actual coordinate and an actual angle of exit of the incoming muons; a detector to measure a momentum of said incoming muons; and, a processing unit, wherein said processing unit: receives threat sensitivity vectors determined from the first stage; operates a positioning system that positions a high-Z threat within the cargo relative to said first and second muon detectors; and, employs said first and second muon information and threat sensitivity vectors to confirm a presence of high-Z materials.

The first stage may be a high energy X-ray cargo inspection system.

The first and second muon detectors may be Thin Gap Chamber (TGC) detectors or Thick Gas Electron Multiplier (THGEM) detectors.

Optionally, the threat sensitivity vectors comprise: a number of suspected high-Z threats; an approximate shape and an approximate size of said suspected high-Z threats; dimensional information, density information, and approximate Z

distribution of the content of said cargo; and an area or a volume of suspected high-Z threats along a path length of a radiation beam employed for scanning said cargo in said first stage.

Optionally, the positioning system comprises: a range sensor to detect a position of the cargo relative to a center of said first and second muon detectors; and an indicator to assist said cargo in attaining said position. Optionally, the indicator comprises at least one of: a traffic light where green indicates a driver to continue moving, yellow to prepare to stop and red to stop said cargo; and a digital display showing the distance to stop said cargo.

Optionally, the positioning system comprises: a range sensor to detect a position of said cargo relative to a center of said first and second muon detectors; and a detector-positioning system to assist said first and second muon detectors in attaining said position.

The second muon detector may be placed inside a trench in a ground below said cargo.

The cargo may be driven over a ramp wherein said second muon detector is placed within the ramp.

The second muon detector may be sized to be placed in a gap between the wheels of said cargo and two sets of muon detectors may be placed on either side of said cargo. The cargo may be raised over two ramps.

The second muon detector may be positioned vertically on one side of said cargo and the second stage system may further comprise a third muon detector positioned vertically on the other side of said cargo. The second stage system may further comprise at least two layers of fourth muon detectors sized to be placed in a gap between wheels of said cargo. The cargo may be raised over two ramps.

Optionally, said second muon detector has a different size than said first muon detector.

Optionally, said first and second muon detectors comprise at least two layers of detectors that are substantially parallel. The at least two layers of first and second muon detectors may be spaced at a distance ranging from approximately 50 mm to 500 mm.

The first and second muon detectors may have dimensions within a range of approximately 2 m×3 m (length) to 3 m×4 m (width). The first and second muon detectors may have dimensions within a range of approximately 3 m×4 m (length) to 3 m×4 m (width).

Optionally, the processor unit resolves the threat alarm by restricting a muon scan data analysis to an area or volume of said high-Z threat along a path length of a radiation beam employed for scanning said cargo in said first stage.

Optionally, the processor unit uses an approximate Z distribution and density of a content of said cargo to compensate for the presence of cargo content in a vicinity of said high-Z threat.

The first stage may be a radiation portal monitor.

The present specification also discloses a second stage screening system to resolve a threat alarm detected in a cargo by a first stage screening system, the second stage screening system comprising: a first muon detector set placed above the cargo to generate first muon threat information and first muon no-threat information; a second muon detector set placed below the cargo to generate second muon threat information and second muon no-threat information; a detector to measure a momentum of said incoming muons; and a processing unit, wherein said processing unit: receives threat sensitivity vectors determined from the first stage; operates a positioning system that centers a high-Z threat location within the cargo relative to said first and second muon detectors to generate said first and second muon threat information; operates the positioning system that centers a second location within the cargo relative to said first and second muon detectors to generate said first and second no-threat information, wherein the second location has no high-Z threat but has density and Z distribution similar to the high-Z threat location; and, employs said first and second muon threat and no-threat information and threat sensitivity vectors to confirm a presence of high-Z threat.

Optionally, said first muon threat information comprises a first coordinate and an angle of incidence of incoming muons and said second muon threat information comprises an actual coordinate and an actual angle of exit of the incoming muons.

Optionally, said first muon no-threat information comprises a first coordinate and an angle of incidence of incoming muons and said second muon no-threat information comprises an actual coordinate and an actual angle of exit of the incoming muons.

Optionally, the processing unit subtracts the first and second muon no-threat information from the first and second muon threat information to confirm the presence of high-Z threat.

The first stage may be a high energy X-ray cargo inspection system.

The first and second muon detectors may be Thin Gap Chamber (TGC) detectors or Thick Gas Electron Multiplier (THGEM) detectors.

Optionally, the threat sensitivity vectors comprise: a number of suspected high-Z threats; an approximate shape and an approximate size of said suspected high-Z threats; dimensional information, density information, and approximate Z distribution of the content of said cargo; and an area or a volume of suspected high-Z threats along a path length of a radiation beam employed for scanning said cargo in said first stage.

Optionally, the positioning system comprises: a range sensor to detect a position of the cargo relative to a center of said first and second muon detectors; and an indicator to assist said cargo in attaining said position. Optionally, the indicator comprises at least one of: a traffic light where green indicates a driver to continue moving, yellow to prepare to stop and red to stop said cargo; and a digital display showing the distance to stop said cargo.

Optionally, the positioning system comprises: a range sensor to detect a position of said cargo relative to a center of said first and second muon detectors; and a detector-positioning system to assist said first and second muon detectors in attaining said position.

The second muon detector may be placed inside a trench in a ground below said cargo.

The cargo may be driven over a ramp wherein said second muon detector is placed within the ramp.

The second muon detector may be sized to be placed in a gap between the wheels of said cargo and two sets of muon detectors may be placed on either side of said cargo. The cargo may be raised over two ramps.

The second muon detector may be positioned vertically on one side of said cargo and the second stage system may further comprise a third muon detector positioned vertically on the other side of said cargo. The second stage system may further comprise at least two layers of fourth muon detectors sized to be placed in a gap between wheels of said cargo. The cargo may be raised over two ramps.

Optionally, said second muon detector has a different size than said first muon detector.

Optionally, said first and second muon detectors comprise at least two layers of detectors that are substantially parallel.

The at least two layers of first and second muon detectors may be spaced at a distance ranging from approximately 50 mm to 500 mm.

The first and second muon detectors may have dimensions within a range of approximately 2 m×3 m (length) to 3 m×4 m (width). The first and second muon detectors may have dimensions within a range of approximately 3 m×4 m (length) to 3 m×4 m (width).

Optionally, the processor unit resolves the threat alarm by restricting a muon scan data analysis to an area or volume of said high-Z threat along a path length of a radiation beam employed for scanning said cargo in said first stage.

Optionally, the processor unit uses an approximate Z distribution and density of a content of said cargo to compensate for the presence of cargo content in a vicinity of said high-Z threat.

The first stage may be a radiation portal monitor.

The first stage may comprise a single or multi-view x-ray scanner.

The first stage may comprise a Radiation Portal Monitor (RPM) comprising a plurality of radiation detectors that detect radiation emitted by radioactive substances within the cargo being inspected. Optionally, the radiation detectors are oriented vertically in the form of a portal enabling cargo to pass there between. The radiation detectors detect gamma, neutron or a combination of gamma and neutron radiation. Accordingly, the radiation detectors comprise plastic scintillator detectors combined with neutron detector blocks, when desired.

The aforementioned and other embodiments of the present specification shall be described in greater depth in the drawings and detailed description provided below.

BRIEF DESCRIPTION OF THE DRAWINGS

These and other features and advantages of the present specification will be appreciated, as they become better understood by reference to the following detailed description when considered in connection with the accompanying drawings, wherein:

FIG. **1**A is a block diagram illustration of a cargo threat detection and alarm resolution system of the present specification;

FIG. **1**B shows an embodiment of a first stage high energy X-ray cargo inspection system;

FIG. **1**C shows an embodiment of a Radiation Portal Monitor (RPM) of the first stage inspection system;

FIG. **1**D shows a first embodiment of a second stage muon detection system;

FIG. **1**E shows a second embodiment of the second stage muon detection system;

FIG. **1**F shows use of scattering layers to measure muon momentum in accordance with an embodiment of the second stage muon detection system;

FIG. **1**G shows a third embodiment of the second stage muon detection system;

FIG. **1**H shows positioning of a cargo for the second stage inspection in accordance with an embodiment;

FIG. **2**A shows a fourth embodiment of the second stage muon detection system;

FIG. **2**B shows a fifth embodiment of the second stage muon detection system;

FIG. **2**C shows a sixth embodiment of the second stage muon detection system;

FIG. **2**D shows a seventh embodiment of the second stage muon detection system;

FIG. **2**E shows an eighth embodiment of the second stage muon detection system;

FIG. **3** is a flow chart illustrating a plurality of exemplary steps of a threat alarm resolution method in accordance with an embodiment; and

FIG. **4** is a flow chart illustrating a plurality of exemplary steps of a threat alarm resolution method, in accordance with another embodiment.

DETAILED DESCRIPTION

For purposes of this specification, cargo refers to crates, trucks, vehicles, land or sea containers, pallets and baggage. In one embodiment, the present specification is directed towards a contraband inspection system and method that efficiently detects and resolves high-Z material alarms, such as, but not limited to, special nuclear material(s) (SNM) (i.e. uranium, plutonium) in an assembled nuclear device; at least one separate quantity of SNM(s) intended for the eventual assembly into a nuclear device; and, one of a number of high-Z materials (e.g. tungsten, lead) typically used to shield radioactive materials to prevent the emitted radiation from being detected by the arrays of passive detectors that are being placed into operation at a number of global ports of entry. Examples of radiation-emitting threats include SNM and radioactive isotopes that could be used in a radiological dispersal device (i.e., "dirty bomb").

The present specification is directed towards multiple embodiments. The following disclosure is provided in order to enable a person having ordinary skill in the art to practice the invention. Language used in this specification should not be interpreted as a general disavowal of any one specific embodiment or used to limit the claims beyond the meaning of the terms used therein. The general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Also, the terminology and phraseology used is for the purpose of describing exemplary embodiments and should not be considered limiting. Thus, the present specification is to be accorded the widest scope encompassing numerous alternatives, modifications and equivalents consistent with the principles and features disclosed. For purpose of clarity, details relating to technical material that is known in the technical fields related to the invention have not been described in detail so as not to unnecessarily obscure the present specification.

FIG. **1**A is a block diagram illustration of a cargo threat detection and alarm resolution system **100** in accordance with an embodiment of the present specification. The system **100** comprises a muon tomography (MT)-based threat alarm resolution system **110** integrated, associated, linked or coupled with a threat detection system **105**. In some embodiments, the threat detection system **105** is operated in a first stage. In some embodiments, the muon tomography system **110** is operated in a second stage. Processor unit **115** uses the data collected from the second stage **110** and the threat detection data from the first stage **105** to confirm or clear a potential threat alarm and to coordinate alignment of the identified threat areas with reference to the second stage muon tomography system **110**. Monitor **120** displays a plurality of processed information from the first stage **105** and/or second stage **110**.

The first and second stages **105**, **110** along with the processor **115** and the monitor **120** are linked through a data communication wired and/or wireless network **102**. While in one embodiment, the first and second stages **105**, **110** are co-located in another embodiment these are remotely located from each other. When the two stages **105**, **110** are placed remotely or at a distance from one another the potential threat alarm scan data from the first stage **105** is communicated to the remotely located second stage **110**. Also, in some embodiments, a cargo vehicle license plate or cargo ID is read using an Optical Character Recognition (OCR) or a similar identification system to allow for matching the cargo scan between the two stages **105**, **110**.

Also, while FIG. **1**A shows a single processing unit **115** linked to both stages **105**, **110** in alternate embodiments the two stages **105**, **110** may have their respective processing units that in turn are linked to each other through a wired and/or wireless network for data communication.

In addition, one of ordinary skill in the art would appreciate that the processing unit **115** comprises any computing platform including, but not limited to: a laptop or tablet computer; personal computer; personal data assistant; cell phone; server; embedded processor; main-frame, DSP chip or specialized imaging device. The threat alarm resolution methods of the present specification are calibrated based on muon scan measurements of a plurality of high-Z materials placed in a plurality of locations within a variety of cargo content and for a plurality of muon momentums. Additionally, the threat alarm resolution methods described herein may be implemented in programmatic code that can be compiled (either pre-compiled or compiled "just-in-time") into a single application executing on a single computer, or distributed among several different computers operating locally or remotely to each other. It should further be appreciated that all of the method steps disclosed herein, including any and all processing or analytical functions, are implemented in such programmatic code stored in a memory and executed on by at least one processor in the computing platform.

In an embodiment, the first stage **105** comprises a high energy X-ray cargo inspection system that scans cargo containers/vehicles at high throughput and determines/detects a presence of areas suspected to contain high-Z materials, including threats such as shielded and un-shielded special nuclear materials (SNM) and radioactive materials. The first stage **105** may employ single, dual or multi-energy, multi-view radiographic imaging systems including those where X-rays or gamma rays, neutrons and both neutrons and X-rays or gamma rays are employed. An advantage of the multi-view radiographic imaging systems is that such systems enable better localization of high-Z threats thereby improving detection at the second stage

FIG. **1**B shows, in accordance with the first stage **105**, a cargo **125** being scanned by a high energy X-ray source **130** such that a fan beam of radiation **135** transmitted through the cargo **125** is captured by detectors **140**. In one embodiment, the detectors **140** are oriented such that they form an L-shape. In one embodiment, the source **130** and detectors **140** are stationary while the cargo **125** is made to move there between. In an alternate embodiment, a scan vehicle with an L-shaped boom carries the source **130** with the detectors **140** mounted on the boom. In this case, the scan vehicle is moved with reference to the cargo **125**, which remains stationary, for inspection. The processor **115** (shown in FIG. **1**A) implements an image processing and threat detection method that processes radiographic scanned image data **126** obtained from the detectors **140** to determine a presence of one or more high-Z threats **145** within the cargo **125**. The image processing and threat detection method is calibrated based on measurements of a plurality of high-Z materials placed in a plurality of locations within a variety of cargo content. An example first stage X-ray cargo inspection system and method is described in US Publication No. 20100295689 which is herein incorporated by reference in its entirety.

The cargo distribution is estimated employing the 2D X-ray image **126** and making assumptions about the depth position of the cargo. For dual-energy X-ray systems, the approximate atomic number can also be inferred. Persons of ordinary skill in the art should appreciate that an exact composition of cargo is not required to compensate for the scattering of the cargo. Therefore, in most cases, these estimates would suffice. For multi-view systems, the cargo estimates are more accurate.

In accordance with an embodiment, the radiographic scan data **126** is processed to extract threat sensitivity vectors such as a) number of 'suspected high-Z' objects/threats, b) a plurality of 'suspected high-Z' parameters such as position/location along the path length of the beam **135**, suspected shape, size and c) a plurality of cargo content parameters such as dimensions, density and approximate density and Z distribution of the cargo content in the vicinity of the 'suspected high-Z' areas/objects.

Referring back to FIG. **1**A, the second stage **110** comprises a passive cosmic-ray muon detection system. Penetrating cosmic-ray muons are a natural radiation background. When they travel through a material, muons deviate from their original trajectory, the extent of the effect depending on the material atomic number Z and thickness, and on the muon particle momentum.

In one embodiment, the first stage **105** comprises a Radiation Portal Monitor (RPM) comprising a plurality of radiation detectors that detect radiation emitted by radioactive substances within the cargo being inspected. FIG. **1**C shows a Radiation Portal Monitor **175** wherein the cargo **125** is being scanned by detectors **140**. In one embodiment, the detectors **140** are oriented vertically in the form of a portal enabling the cargo **125** to pass there between. The detectors **140** detect gamma, neutron or a combination of gamma and neutron radiation. Accordingly, the detectors **140** comprise gamma-ray detectors combined with neutron detector blocks, when desired. Example Radiation Portal Monitors include TSA TM850 and TSA VM250 by Rapiscan Systems Inc. The processor **115** (shown in FIG. **1**A) implements an image processing and threat detection method that processes radiation scan data obtained from the detectors **140** to determine the presence of special nuclear material **145** within the cargo **125**.

FIG. **1**D shows the second stage **110** wherein a single layer muon detector or at least two layers of substantially parallel muon detectors **150** separated by a distance 'd.', such as that ranging from approximately 50 mm to 500 mm, and preferably 400 mm, are placed on top of the cargo **125** to detect a direction or angle of incidence of incident muons **155**. An additional single layer muon detector or at least two additional layers of substantially parallel muon detectors **160** are placed below the cargo **125** to detect a muon scattering angle or an angle of exit of the scattered muons **156**. In one embodiment the dimensions of the detectors ranges from approximately 2 m×3 m (length) to 3 m×4 m (width) so as to enable capturing incident and scattered muons. In other embodiments, where the first stage **105** comprises a Radiation Portal Monitor (as shown in FIG. **1**C), the dimensions of the detector **150**, **160** ranges from approximately 3 m×4 m (length) to 3 m×4 m (width). In a preferred embodiment, the muon detectors are Thin Gap Chamber (TGC) detectors or Thick Gas Electron Multiplier (THGEM). However, in various alternate embodiments other types of detectors can be used, such as for example—cylindrical proportional counters with pulse shape discriminating readout to maximize spatial resolution. In one embodiment, the bottom detectors **160** are placed inside a trench **165** dug in the ground. This embodiment is useful for fixed second stage sites.

FIG. **1**E shows another embodiment, where the cargo **125**, comprising a 'suspected high-Z' threat area **146**, is driven over a ramp **170** with the detectors **160** placed inside the ramp **170** and with detectors **150** at the top. This embodiment is more suitable when a trench is not desired due to reasons such as low water table, need for a relocatable system, cost, etc. FIG. **1**G shows yet another embodiment where the lower detectors **160** are smaller to reduce cost and reduce installation requirements.

The number and orientation of the muon detectors can vary in accordance with a plurality of embodiments. For example, in one embodiment shown in FIG. **2**A two muon detectors **250** are placed horizontally at the top while small muon detector layers **260** are placed in the gap between the wheels of the cargo **225**. In this case the distance between the detector layers **260** is less thereby reducing the angular resolution. FIG. **2**B shows an improved embodiment wherein apart from using the top detectors **250**, two low-height ramps **270** (approximately 20 cm to 50 cm in height) are used to raise the cargo vehicle **225** to allow the required spacing between the layers of the bottom detectors **260**. These ramps are made for example, of aluminum honeycomb, to reduce weight and facilitate relocation. In one embodiment, the top muon detectors **250** are mounted on a horizontal boom of a muon scanning vehicle. In an additional embodiment, as shown in FIG. **2**B, two sets of detectors **240** are additionally placed on each side of the cargo vehicle **225** to increase the detection efficiency. The advantage of the embodiments shown in FIGS. **2**A and **2**B is a reduction of site modifications, with some increase of scan time due to a loss of efficiency.

FIG. **2**C shows another embodiment where apart from the top horizontal muon detectors **250** additional muon detectors **265***a*, **265***b* are placed vertically at both sides of the cargo **225**. In an embodiment, the vertical detector **265***a* is installed on a side of a muon scanning vehicle while the detectors **250** and **265***b* are mounted on a horizontal and vertical boom of the scanning vehicle. Alternatively, the detectors **250**, **265***a*, **265***b* are mounted on a mobile gantry. Improved muon detection efficiency is achieved if apart from the detectors **250**, **265***a*, **265***b*—small muon detectors **275** are additionally placed in the gap between the wheels of the cargo **225**, as shown in FIG. **2**D. However, in this case the distance between the detector layers **275** is less thereby reducing the angular resolution. Therefore, in an alternate embodiment, two low-height ramps **280** (approximately 20 cm to 50 cm in height) are used to raise the cargo **225** and allow the required spacing between the layers of the detectors **275** as shown in FIG. **2**E. The configuration of detectors **250**, **265***a*, **265***b* remains same across the embodiments of FIGS. **2**C, **2**D and **2**E.

Referring back to FIG. **1**D, the threat sensitivity vectors (from the first stage **105**) are utilized advantageously by the second stage **110** to efficiently and effectively resolve threat alarms. For example, the number and position of 'suspected high-Z' threats (of the threat sensitivity vectors) are used to move and position the cargo **125** in such a way that the 'suspected high-Z' threat **145** (within the threat area/volume **146**) is centered at the detectors **150** and **160**, at which time a stationary and passive muon scan is performed. If there are more than one 'suspected high-Z' threat areas, the above process of threat area alignment with reference to the detectors **150**, **160**, is repeated. If some or all of the suspected threats are grouped close to each other (such as being less than 0.5 m apart), the detectors **150**, **160** are centered at the approximate center of the suspected threats. In one embodiment, the processor **115**, shown in FIG. **1**A, uses the threat sensitivity vectors to coordinate the operation of a cargo positioning system to enable proper alignment of the 'suspected high-Z' threat areas **146** within the cargo **125** with reference to the detectors **150**, **160**.

The cargo positioning system, in one embodiment, comprises a range sensor that detects the position of the cargo **125** relative to the center of the muon detectors **150**, **160**. Using the position of the 'suspected high-Z' threat **145** (within the threat area/volume **146**) obtained from the primary system/first stage **105**, an indicator notifies the cargo vehicle driver to stop the cargo where the 'suspected high-Z' alarming threat area(s) is at the approximate center of the muon detectors. In one embodiment, the indicator comprises a traffic light where green indicates to continue moving, yellow to prepare to stop and red to stop. The indicator may also include a digital display that shows the cargo driver the distance to stop. FIG. **1**H shows, according to an example, the positioning of the cargo **125** when the first stage **105** provides three dimensional (3D) localization information of the 'suspected high-Z' threat **145**. In addition to locating the plane **147** of the threat **145** at the center of the muon detectors **150**, **160** (detector **160** being located in a trench **165** in accordance with the embodiment of FIG. **1**D) in the direction of motion, the cargo **125** is also positioned in such a way that the threat **145** is centered laterally with reference to the muon detectors **150**, **160**.

Unlike active interrogation systems, the muon-based detection system being passive enables the cargo driver to stay on the truck, reducing the overhead time to have the driver get off and back on, thereby obviating a need for mechanical systems to move the cargo/container.

In another embodiment, the cargo is stationary and the detectors are moved to be centered at the location of the suspect threat/object. In this embodiment the detectors are housed in a truck ramp to enable appropriate positioning relative to the suspected threat location.

The first muon detectors **150** measure the muon incidence angle and muon incidence coordinate while the second muon detectors **160** measure the actual muon exit angle and muon exit coordinate. In addition to the Z of the materials, the muon deflection/scatter angles also depend on the momentum of the incoming muons, with low-energy muons (e.g. <1 GeV) generating larger deflection/scatter angles than the high-energy muons. Therefore, a measurement of the muon momentum reduces the Z uncertainty. In one embodiment, the low energy muon momentum is also determined by measuring the muon velocity derived from the distance and time of flight between the upper and lower detectors **150**, **160**.

Another possibility to measure the momentum of the muon is to add scattering layers below the lower detectors **160**. As illustrated in FIG. **1**F, each scattering layer is built from a layer of lead **166** attached to the muon detector layer above **160***a*, an empty space **160***b* (e.g. 25 cm) and another detector layer **160***c*. The number of scattering layers and the amount of lead define the range and accuracy of the momentum measurements possible with such a detector [as described in L. Shultz, Ph.D. thesis, Portland State University, 2003]. It should be appreciated that the use of scattering layers can be implemented as part of the trench (of FIG. **1**D) or the ramp (as shown in FIG. **1**F). The empty space **160***b* between the scattering layer and the detector **160***c* positioned below it can be increased to allow the use of detectors with lower spatial resolution.

The processor **115**, shown in FIG. **1**A, implements a threat alarm resolution method of the present specification that, in one embodiment, uses the coordinate and incidence angle parameters for each muon measured at the top detector layers

150 to calculate the expected muon coordinate and exit angle parameters at the bottom detector layers **160**. A distribution of the deflection/scatter angles, calculated according to the measurements of the actual incident and exit angles, are compared with the expected parameters. If the deviation between the actual and expected parameters is greater than or equal to a predetermined threshold scattering angle then the second stage **110** confirms the threat alarm determined by the first stage **105** and an audio/visual alarm is generated. However, if the deviation between the actual and expected parameters is below the predetermined threshold then the second stage **110** clears the threat alarm. In one embodiment, the predetermined threshold scattering angle ranges from 1 to 100 milliradian. In other embodiments, if the deflection/scattering angle distribution has an excess of large angle scattering events, then the second stage **110** confirms the threat alarm determined by the first stage **105**. Also, alternate embodiments use reconstruction algorithms such as, but not limited to, point of closest approach (POCA) or expectation maximization (EM) to determine the point(s) of muon interaction within the cargo and angle(s) of deflection/scatter. POCA takes the muon's entry and exit coordinates, constructs the entry and exit trajectory, then calculates the line of shortest distance between them and the midpoint of that line is taken to be where scattering took place. This point is given the name POCA point. EM reconstruction uses an iterative method. It takes both scattering angle and linear deviation as input. Then it distributes the scattering location along the POCA track and thereafter determines the maximum likelihood of scattering over voxels.

One of the issues for detecting high-Z materials in cargo is that cargo materials could be dense and occupy a large volume of the cargo container. This results in many small-angle scatters that could be confused with high-Z materials in a lightly loaded cargo. Also, the high-Z materials located at different parts of the cargo result in different muon scatter responses. Therefore, it is highly desirable to have knowledge of the cargo material and distribution, and approximate location of the high-Z materials to compensate for the issues related to cargo material and distribution.

In an embodiment that addresses these issues, the threat alarm resolution method of the present specification additionally utilizes the threat sensitivity vectors of the first stage **105** by a) correlating the 'suspected high-Z' parameters such as position/location, shape and size determined in the first stage **105** with the muon scan data in the second stage **110** and b) building a reference for distribution of muon deflections by employing the cargo content parameters such as dimensions, density and approximate Z distribution of the cargo content in the vicinity of the 'suspected high-Z' areas/objects. Persons of ordinary skill in the art would appreciate that in prior art primary muon measurement systems, the image reconstruction is performed to determine the location of the high-Z materials within the complete volume of the cargo. However, in the threat alarm resolution method of the present specification, the volume to analyze (or the muon scan data to be analyzed) is only the one along the path length of the beam. Also, the X-ray scan image provides useful information about the cargo density and atomic-number (Z) distribution that is used to compensate for the presence of neighboring material. Thus, in this embodiment apart from using the deviation of actual and expected parameters to resolve threat alarms, the threat alarm resolution method of the present specification utilizes the threat sensitivity vectors of the first stage **105** to further improve robustness and effectiveness of the threat alarm resolution thereby reducing false positive alarm rates.

Accordingly, in one embodiment, the muon measurements (that is, the muon incidence angle and the muon incidence coordinate of an incoming muon at the first muon detectors **150** and the actual muon exit angle and the mount exit coordinate of the incoming muon at the second muon detectors **160**) are performed at a first and a second location. The first location corresponds to the 'suspected high-Z' threat **145** while the second location is taken (different from the first location) where there is cargo similar to the cargo around the 'suspected high-Z' threat **145** but without the threat. The muon results at the second location, without the threat, are used to compensate for the cargo scattering. In addition, the constraint consisting of the threat location along the path of the radiation is used to improve detection.

A plurality of methods can be used to derive threat alarms from the muon measurements. FIG. **3** is a flow chart illustrating a plurality of exemplary steps of a threat alarm resolution method, in accordance with an embodiment, implemented by at least one processor in data communication with a first stage threat detection system and a second stage muon threat alarm resolution system. At step **305**, a plurality of threat sensitivity vectors, with reference to a cargo under inspection, are received from the first stage threat detection system. The plurality of threat sensitivity vectors comprise data such as, but not limited to, a) number of 'suspected high-Z' objects/threats in the cargo, b) a plurality of 'suspected high-Z' parameters such as position/location, suspected area/volume, shape, size and c) a plurality of cargo content parameters such as dimensions, density and approximate density and Z distribution of the cargo content in the vicinity of the 'suspected high-Z' areas/objects. The plurality of threat sensitivity vectors are utilized, at step **315**, to align the 'suspected high-Z' threat areas (within the cargo) with reference to a first and second muon detectors placed above and below the cargo, respectively, in the second stage muon threat alarm resolution system.

Thereafter, at step **325**, a first coordinate and an angle of incidence of an incoming muon are detected at the first muon detectors. At step **335**, the first coordinate and angle of incidence are used to calculate an expected/estimated second coordinate and an expected/estimated angle of exit of the incoming muon at the second muon detectors. In one embodiment, a momentum of the incoming muon is used as a filter to improve an accuracy of the expected/estimated second coordinate and angle of exit of the incoming muon. Next, an actual coordinate and an actual angle of exit of the incoming muon are detected at the second muon detectors, at step **345**. Now, at step **355**, a deviation (that is, an angle of deflection/scatter) of the actual coordinate and actual angle of exit with reference to the expected/estimated coordinate and expected angle of exit is calculated. In accordance with an embodiment, a statistical distribution of the deviations for a plurality of incoming muons is determined (also referred to as 'deviation distribution'). It should be appreciated that alternate embodiments use reconstruction algorithms such as point of closest approach (POCA) or expectation maximization (EM) to determine the point(s) of muon interaction within the cargo and angle(s) of deflection/scatter (that is, the deviation of the actual angle of exit with reference to the expected/estimated angle of exit of the muons).

In another embodiment, apart from performing steps **315** to **355** corresponding to 'suspected high-Z threat' areas (within the cargo), steps **315** to **355** are repeated for at least one second location (different from the 'suspected high-Z threat' areas) where there is cargo similar (in terms of density and Z distribution) to the cargo around the 'suspected high-Z' threat but without the threat. In other words, step **315** is repeated to have the at least one second location aligned with reference to the first and second muon detectors. Thereafter, steps **325** to **355** are also repeated to generate muon information corresponding to the second location. In this embodiment, the muon information (that is, a first coordinate and an angle of incidence of an incoming muon at the first muon detectors and an actual coordinate and an actual angle of exit of the incoming muon at the second muon detectors) at the second location, without the threat, is used to compensate for cargo scattering.

At step **365**, if the deviation (or the statistical distribution thereof) is greater than or equal to a predetermined threshold then the 'suspected high-Z' threat is confirmed. On the other hand, if the deviation (or the statistical distribution thereof) is below the predetermined threshold then, at step **375**, the 'suspected high-Z' threat is cleared. In an alternate embodiment, if the deviation or a distribution of the angles of deflection/scatter has an excess of large angle scattering events, then the 'suspected high-Z' threat is confirmed.

FIG. **4** is a flow chart illustrating a plurality of exemplary steps of a threat alarm resolution method, in accordance with various other embodiments, implemented by at least one processor in data communication with the first stage threat detection system and the second stage muon threat alarm resolution system. As in the method of FIG. **3**, a plurality of threat sensitivity vectors are obtained from the first stage threat detection system, at step **400**. At step **410**, the threat sensitivity vectors are advantageously utilized to align the muon detectors with reference to the suspected high-Z threats, in the second stage muon threat alarm resolution system. Thereafter, at step **420** the locations/coordinates and directions of the muons are recorded upon entering and leaving a scanned volume, along with any measurements of the muon momentum.

In one embodiment, aimed at detecting compact threats, a 3D scattering density map is reconstructed at step **430**, wherein scattering density is defined as the mean square scattering expected for muons of some nominal momentum per unit depth. In a preferred embodiment, the 3D scattering density map is binned uniformly in each dimension, yielding 3D "voxels", each with its own (average) scattering density. In some cases a 2D scattering density map is preferred, which is then built up of 2D pixels. A simplified statistical model of cosmic muons and their interaction with the materials within the scanned volume is used to find the most likely scattering density map (also known as the solution of maximal likelihood). However the model used in prior art may be too simplistic for "medium-heavy cargo", which both makes the solution of the simplified model less useful and makes it harder to converge to this solution. Also, a typical cargo slows down a muon by 0.5-1.5 GeV, depending on the content of the cargo in the suspected region identified by the first stage.

Therefore, the present invention utilizes 2D and/or 3D mass density maps obtained, at step **405**, from the first stage threat detection system. The average mass density and the average scattering density can vary independently. Thus the measured mass-density cannot be used as direct indication of the scattering-density. From the mass density maps obtained at step **405** and the muon momentum measurements obtained at step **420**, the expected energy loss of the muon is calculated as the muon traverses the scanned volume. At step **425**, the expected energy loss is then used to calculate the expected muon momentum at each point along its path/trajectory. The expected muon momentum is thereafter incorporated in the statistical model which is used to reconstruct the scattering density map at step **430**.

Another utilization of the mass density map (obtained at step **405**) is at step **415** to identify regions where the mass density is particularly low, e.g. similar to that of air. This implies that the scattering density in such identified regions is also particularly low, and this information is then incorporated in the statistical model used to find the scattering density map at step **430**. Such scenarios of particularly low mass density are common in medium-heavy cargo which is often packed at the bottom of the cargo, leaving the top of the scanned volume empty.

Yet another utilization of the mass density map (obtained at step **405**) is at step **435** to identify a candidate scattering density map, which serves as a starting seed for reconstructing/solving the statistical inference model/problem of step **430**. An identified starting seed reduces computing time and increases the reliability of converging to a correct statistical inference solution. It is also advantageous to reframe the statistical inference problem in terms of deviations from, or ratio to, the candidate scattering density map. A preferred approach to identification of the candidate scattering density map is via a database of cargos whose mass and scattering densities have been measured in controlled conditions. Alternatively, the candidate scattering density map can be calculated from the mass density map.

As the location of threat is not expected to align with the voxels, a threat will typically increase the densities measured in several adjacent voxels. Such local deviations can be identified, at step **440**, by summing up and filtering adjacent voxels. Both the scattering density map and these local deviations are then inspected visually, at step **450**, and an alarm is automatically raised at step **465** based on the statistical significance of the local deviations or, possibly in cooperation with the operator, the cargo is cleared at step **460** in case the local deviations are found to be statistically insignificant.

The mass density maps obtained at step **405** can also be used independently of any mapping. In one embodiment a distribution of an observable, such as the scattering angle or the number of outgoing muons (from step **420**), is tracked for a specific class of muons, for example those with a low scattering deflection (from step **420**), and compared to a reference distribution. The reference distribution is derived, at step **445**, from a database using the measured mass density map to identify similar cargos. At step **455**, the deviations in selected distributions are quantified and used to automatically raise an alarm (at step **465**) or, possibly in cooperation with the operator, to clear the cargo (at step **460**).

The above examples are merely illustrative of the many applications of the system of present invention. Although only a few embodiments of the present invention have been described herein, it should be understood that the present invention might be embodied in many other specific forms without departing from the spirit or scope of the invention. Therefore, the present examples and embodiments are to be considered as illustrative and not restrictive, and the invention may be modified within the scope of the appended claims.

We claim:

1. A second stage screening system to resolve a threat alarm detected in a cargo by a first stage screening system, wherein said first stage screening system generates threat sensitivity vectors, said second stage system comprising:

a first muon detector set placed above the cargo to generate first muon information comprising a first coordinate and an angle of incidence of incoming muons;

a second muon detector set placed below the cargo to generate second muon information comprising an actual coordinate and an actual angle of exit of the incoming muons;

a detector to measure a momentum of said incoming muons; and,

a processing unit, wherein said processing unit:

receives threat sensitivity vectors determined from the first stage;

operates a positioning system that positions a high-Z threat within the cargo relative to said first and second muon detectors;

employs said first and second muon information and threat sensitivity vectors to confirm a presence of high-Z materials; and

uses an approximate Z distribution and density of a content of said cargo to compensate for a presence of cargo content in a vicinity of said high-Z threat.

2. The second stage system of claim **1**, wherein said first and second muon detectors are Thin Gap Chamber (TGC) detectors.

3. The second stage system of claim **1**, wherein said first and second muon detectors are Thick Gas Electron Multiplier (THGEM) detectors.

4. The second stage system of claim **1**, wherein said threat sensitivity vectors comprise:

a number of suspected high-Z threats;

an approximate shape and an approximate size of said suspected high-Z threats;

dimensional information, density information, and approximate Z distribution of the content of said cargo; and

an area or a volume of suspected high-Z threats along a path length of a radiation beam employed for scanning said cargo in said first stage.

5. The second stage system of claim **1**, wherein the positioning system comprises:

a range sensor to detect a position of the cargo relative to a center of said first and second muon detectors; and

an indicator to assist said cargo in attaining said position.

6. The second stage system of claim **5**, wherein said indicator comprises at least one of:

a traffic light where green indicates a driver to continue moving, yellow to prepare to stop and red to stop said cargo; and

a digital display showing the distance to stop said cargo.

7. The second stage system of claim **1**, wherein the positioning system comprises:

a range sensor to detect a position of said cargo relative to a center of said first and second muon detectors; and

a detector-positioning system to assist said first and second muon detectors in attaining said position.

8. The second stage system of claim **1**, wherein said second muon detector is placed inside a trench in a ground below said cargo.

9. The second stage system of claim **1**, wherein said cargo is driven over a ramp and wherein said second muon detector is placed within the ramp.

10. The second stage system of claim **1**, wherein said second muon detector is sized to be placed in a gap between the wheels of said cargo and two sets of muon detectors are placed on either side of said cargo.

11. The second stage system of claim **10**, wherein said cargo is raised over two ramps.

12. The second stage system of claim **1**, wherein said second muon detector is positioned vertically on one side of said cargo and further comprising a third muon detector positioned vertically on the other side of said cargo.

13. The second stage system of claim **12**, further comprising at least two layers of fourth muon detectors sized to be placed in a gap between wheels of said cargo.

14. The second stage system of claim **12**, wherein said cargo is raised over two ramps.

15. The second stage system of claim **1**, wherein said second muon detector has a different size than said first muon detector.

16. The second stage system of claim **1**, wherein said first and second muon detectors comprise at least two layers of detectors that are parallel.

17. The second stage system of claim **16**, wherein said at least two layers of first and second muon detectors are spaced at a distance ranging from approximately 50 mm to 500 mm.

18. The second stage system of claim **1**, wherein said first and second muon detectors have dimensions within a range of approximately 2 m×3 m (length) to 3 m×4 m (width).

19. The second stage system of claim **1**, wherein said first and second muon detectors have dimensions within a range of approximately 3 m×4 m (length) to 3 m×4 m (width).

20. The second stage system of claim **1**, wherein said processor unit resolves the threat alarm by restricting a muon scan data analysis to an area or volume of said high-Z threat along a path length of a radiation beam employed for scanning said cargo in said first stage.

21. The second stage of claim **1**, wherein said first stage is a radiation portal monitor.

22. A second stage screening system to resolve a threat alarm detected in a cargo by a first stage screening system, the second stage screening system comprising:

a first muon detector set placed above the cargo to generate first muon threat information and first muon no-threat information;

a second muon detector set placed below the cargo to generate second muon threat information and second muon no-threat information;

a detector to measure a momentum of said incoming muons; and

a processing unit, wherein said processing unit:

receives threat sensitivity vectors determined from the first stage;

operates a positioning system that centers a high-Z threat location within the cargo relative to said first and second muon detectors to generate said first and second muon threat information;

operates the positioning system that centers a second location within the cargo relative to said first and second muon detectors to generate said first and second no-threat information, wherein the second location has no high-Z threat but has density and Z distribution similar to the high-Z threat location; and,

employs said first and second muon threat and no-threat information and threat sensitivity vectors to confirm a presence of high-Z threat.

23. The second stage system of claim **22**, wherein said first muon threat information comprises a first coordinate and an angle of incidence of incoming muons and wherein said second muon threat information comprises an actual coordinate and an actual angle of exit of the incoming muons.

24. The second stage system of claim **22**, wherein said first muon no-threat information comprises a first coordinate and an angle of incidence of incoming muons and wherein said second muon no-threat information comprises an actual coordinate and an actual angle of exit of the incoming muons.

25. The second stage system of claim **22**, wherein the processing unit subtracts the first and second muon no-threat information from the first and second muon threat information to confirm the presence of high-Z threat.

26. The second stage system of claim **22**, wherein said first and second muon detectors are Thin Gap Chamber (TGC) detectors.

27. The second stage system of claim **22**, wherein said first and second muon detectors are Thick Gas Electron Multiplier (THGEM) detectors.

28. The second stage system of claim **22**, wherein said threat sensitivity vectors comprise:

a number of suspected high-Z threats;

an approximate shape and an approximate size of said suspected high-Z threats;

dimensional information, density information, and approximate Z distribution of the content of said cargo; and

an area or a volume of suspected high-Z threats along a path length of a radiation beam employed for scanning said cargo in said first stage.

29. The second stage system of claim **22**, wherein the positioning system comprises:

a range sensor to detect a position of the cargo relative to a center of said first and second muon detectors; and

an indicator to assist said cargo in attaining said position.

30. The second stage system of claim **29**, wherein said indicator comprises at least one of:

a traffic light where green indicates a driver to continue moving, yellow to prepare to stop and red to stop said cargo; and

a digital display showing the distance to stop said cargo.

31. The second stage system of claim **22**, wherein the positioning system comprises:

a range sensor to detect a position of said cargo relative to a center of said first and second muon detectors; and

a detector-positioning system to assist said first and second muon detectors in attaining said position.

32. The second stage system of claim **22**, wherein said second muon detector is placed inside a trench in a ground below said cargo.

33. The second stage system of claim **22**, wherein said cargo is driven over a ramp and wherein said second muon detector is placed within the ramp.

34. The second stage system of claim **22**, wherein said second muon detector is sized to be placed in a gap between the wheels of said cargo and two sets of muon detectors are placed on either side of said cargo.

35. The second stage system of claim **34**, wherein said cargo is raised over two ramps.

36. The second stage system of claim **22**, wherein said second muon detector is positioned vertically on one side of said cargo and further comprising a third muon detector positioned vertically on the other side of said cargo.

37. The second stage system of claim **36**, further comprising at least two layers of fourth muon detectors sized to be placed in a gap between wheels of said cargo.

38. The second stage system of claim **36**, wherein said cargo is raised over two ramps.

39. The second stage system of claim **22**, wherein said second muon detector has a different size than said first muon detector.

40. The second stage system of claim **22**, wherein said first and second muon detectors comprise at least two layers of detectors that are parallel.

41. The second stage system of claim **40**, wherein said at least two layers of first and second muon detectors are spaced at a distance ranging from approximately 50 mm to 500 mm.

42. The second stage system of claim **22**, wherein said first and second muon detectors have dimensions within a range of approximately 2 m×3 m (length) to 3 m×4 m (width).

43. The second stage system of claim **22**, wherein said first and second muon detectors have dimensions within a range of approximately 3 m×4 m (length) to 3 m×4 m (width).

44. The second stage system of claim **22**, wherein said processor unit resolves the threat alarm by restricting a muon scan data analysis to an area or volume of said high-Z threat along a path length of a radiation beam employed for scanning said cargo in said first stage.

45. The second stage system of claim **22**, wherein said processor unit uses an approximate Z distribution and density of a content of said cargo to compensate for the presence of cargo content in a vicinity of said high-Z threat.

46. The second stage of claim **22**, wherein said first stage is a radiation portal monitor.

* * * * *